IRRIGATION PRACTICE AND ENGINEERING

VOLUME I

USE OF IRRIGATION WATER

AND

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PREFACE

This volume is the first of a three-volume series covering Irrigation Practice and Engineering. Volume I deals mainly with irrigation practice; Volumes II and III cover the engineering features of irrigation systems. In the preparation of these volumes the authors have endeavored to meet the needs of teachers and students in courses in these subjects and also to present the material in a form that will be useful to those engaged in the construction or management of irrigation systems. The authors have been guided in their selection and presentation of the material both by their experience as teachers of these subjects for many years at the University of California, and by their professional practice extending into nearly all of the states in western United States.

The importance of the agricultural phases of irrigation in the design and management of irrigation systems is now so well recognized that no comment on the appropriateness of including irrigation practice with irrigation engineering in a single series of books is required. Consideration of the service requirements of irrigation systems is as essential to their proper design as is determination of loads in building or bridge design or traffic surveys in highway engineering.

This volume is limited almost wholly to irrigation practice in the United States. While there is much of interest to be learned from the practice of other countries, essential differences, where they occur, are due to differences in climatic or economic conditions, which make the results of experience elsewhere of limited application here.

The first edition of this series was prepared by Mr. Etcheverry in 1914 and 1915. Volume I has been entirely rewritten for this second edition. Although the revisions of Volumes II and III are planned, they have not yet been completed. The larger part of the work of revision of Volume I has been assumed by Mr. Harding. The general arrangement followed is similar to that used in the first edition. During the period since the publication of the first edition, the principles of irriga-

tion practice have not changed materially but knowledge regarding such principles has been broadened with some resulting changes in their application. Present knowledge regarding soil-moisture properties rests on a much broader basis of experimental work than was available at the time the first edition was prepared. Economic conditions have resulted in changes in the character of farm structures and in the use of water. Experience has caused changes in the types of equipment used in pumping. The changes from the first edition are mainly in the examples used to illustrate the principles of practice with some changes in the applications rather than in the scope of the treatment of the subject. The revision represents a complete rewriting of the first edition, however.

An adequate treatment of any subject relating to practice is necessarily largely a compilation of the results of many workers in the field. The quality of a book on practice depends mainly on the thoroughness with which the authors have covered the field and the judgment and discretion used in assembling and arranging the material so as to bring out the essentials without an excess of local detail. The present volume does not attempt to present an inventory of irrigation practice in the United States. Its purpose is to present the essential features of good irrigation practice with sufficient material regarding the subjects involved to support the principles set forth. Results of individual experiments or local practice have been used to illustrate the principles of practice without attempting to describe the conditions and practices of all localities.

The treatment of irrigation practice in this volume is limited to the handling and use of water on the farm. The relationships of the landowner to the different forms of organizations that may construct and operate the canal systems from which he receives water and the basis of water supply and title to its use are subjects of importance to the landowners but are outside the scope of this volume. Pumping from ground water is included as this is a source of water supply provided by each landowner independent of group action. Measurement of water has not been included, although this is a subject properly within the interests of the landowner. Practically all of the agricultural experiment stations of the western states have published bulletins descriptive of the measurement of irrigation water, so that it seemed unnecessary to add such a chapter here. Measurement

of water from the point of view of both the canal organization and the landowner is discussed in Volume III.

While this volume is presented for use as a textbook in courses in the field of irrigation practice, questions and problems for class use have not been included. In the authors' own teaching experience, it has been found that such material readily suggests itself in the handling of this subject. We have found the use of contour maps of selected types of topography particularly useful in problems on land preparation and have prepared and used such maps 8½ by 11 inches in size for such purposes. Numerical problems on soil moisture, conversions from units of volume to rates of flow, selection of sizes of farm conveyance channels and of structures, and examples in pumping plants can be readily prepared to fit the conditions applicable to the conditions in the different states.

Publications on irrigation practice, particularly by state and Federal experiment stations, have been numerous in recent years. Present experiments are more carefully planned and consistently carried out than in the earlier years of such work. This is a natural development. In the earlier periods of scarcity of information nearly all results were useful; now the demand is for much more complete consideration of all the elements involved.

In the preparation of this volume the authors have utilized the published materials, the unpublished results of their own and others' work, as well as many helpful personal suggestions of those active in this field. Where specific results have been taken from a definite source, acknowledgment has been made in the text. Lists of the references quoted are given at the end of each chapter. Such acknowledgments cannot, however, cover all the assistance obtained by the authors as many of the conclusions and recommended practices are the composite result of many sources and contacts. For such assistance the authors acknowledge their obligation and their gratitude.

B. A. Etcheverry.
S. T. Harding.

Berkeley, Calif.
February, 1933.

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USE OF IRRIGATION WATER AND IRRIGATION PRACTICE

CHAPTER I

DEFINITIONS AND CONDITIONS AFFECTING IRRIGATION

Irrigation is the artificial application of water to lands whenever the rainfall is insufficient to meet the full water requirements of crops. This definition, which is similar to that used by a number of writers, includes the elements that distinguish irrigation from the other methods of supplying the moisture needs of crops. Irrigation is supplemental to other sources of moisture supply. It is artificial as distinguished from the natural such as rainfall.

Actual irrigation practice varies from supplying all of the moisture requirements of crops in areas of practically no rainfall, such as in the Imperial Valley in California, to supplying what may be used only at occasional periods of drought in areas where the usual precipitation is sufficient for crop needs. The chief purpose in all cases is to supply the water required to produce the most economical crop yield. Less than an adequate moisture supply results in reduced yields, excessive supplies may also result in reduction in yield and in need for drainage with injury from alkali. Moisture made available to crops from natural precipitation is as useful as an equal amount made available by irrigation. Irrigation should be planned to supplement the moisture received from rainfall.

HISTORY AND EXTENT OF IRRIGATION

Irrigation has been practiced wherever climatic conditions made it an essential part of agriculture. Traces of former systems are found in many countries and areas are now irrigated which have been irrigated by civilizations prior to those now

occupying the lands. There are traces of such early irrigation systems in Arizona and New Mexico in the United States. Remains of similar old systems are found in parts of Asia, Africa, and South America.

The earliest irrigation in the United States resulting from the present settlement of the West was that practiced in connection with the missions in California. Such practice was, however, only incidental to the main purpose of the missions. Other irrigation, also largely incidental, followed in connection with mining or trading settlements. The first western agricultural settlement, located where irrigation was essential, was that of the Mormons in Salt Lake Valley in 1847.

Irrigation has continued to increase, although the rate of increase has varied widely with economic conditions. Earlier developments were in small units using the resources of individuals or small groups. Developments requiring outside financing were important in the eighties and early nineties, became less active during the nineties, and resumed activity from 1902 to about 1910 following the adoption of a policy of construction of irrigation works by the Federal Government. A period of reduced rate of development following 1910 was changed to one of increased activity during and following the World War.

Irrigation has shown the same reduction in new development during the depression in agriculture following this period that has been shown in other lines of agricultural activity. These conditions are reflected in the following figures showing the results of the U. S. Census of Irrigation.

Year	Total area irrigated in the United States, acres	Average increase per year, acres
1889	3,631,381	
		415,080
1899	7,782,188	
		568,300
1902	9,487,077	
		706,600
1909	14,433,285	
		475,840
1919	19,191,716	
		35,580
1929	19,547,544	

The areas irrigated in the world as given in a bulletin on Foreign Markets for Irrigation Machinery and Equipment published by the U. S. Department of Commerce in 1929 total about 200,000,000 acres as shown in the following table:

Continent	Total Area Irrigated, Acres
North America	26,834,000
South America	6,613,000
Europe	14,800,000
Asia	140,754,000
Africa	10,310,000
Oceania	1,270,000
Total	200,581,000

Of the areas irrigated in North America, about 75 per cent are in the United States and 20 per cent in Mexico. The principal areas in South America are in Argentina, Chile, and Peru. In Europe the largest area (6,000,000 acres) is in France, with 3,900,000 acres in Italy, and 3,500,000 acres in Spain. In Asia about 56,000,000 acres were reported in India, 50,000,000 in China, 8,000,000 acres each in Java and in Asiatic Russia, and 7,000,000 acres in Japan with smaller amounts in several other countries. In Africa about one-half of the total area is in Egypt, other important areas being in Madagascar, Morocco, and Union of South Africa.

In the United States, of the different states, California has the largest area irrigated, with Colorado second. The other western states follow with such individual areas as their total area, water supply, and economic conditions have permitted them to develop. Relatively small areas are irrigated in the semi-arid states. The areas irrigated in 1919 and 1929 in the 19 states included in the U. S. Census of Irrigation are as shown on page 4.

For some of the states listed in the following table, irrigation represents only a minor part of the total agricultural development. In Nebraska and Texas irrigation while fairly extensive in some portions of each state is not a large part of its general agriculture. For the 11 principal irrigated states of Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming, the total area irrigated in 1929 of 17,463,960 acres represents only 2.3 per cent of the gross land area.

State	Area irrigated, acres		Change, per cent
	1919	1929	
Arizona	467,565	575,590	+23.1
Arkansas	143,946	151,787	+ 5.4
California	4,219,040	4,746,632	+12.5
Colorado	3,348,385	3,393,619	+ 1.4
Idaho	2,488,806	2,181,250	−12.4
Kansas	47,312	71,290	+50.7
Louisiana	454,882	450,901	− 0.9
Montana	1,681,729	1,594,912	− 5.2
Nebraska	442,690	532,617	+20.3
Nevada	561,447	486,648	−13.3
New Mexico	538,377	527,033	− 2.1
North Dakota	12,072	9,392	−22.2
Oklahoma	2,969	1,573	−47.0
Oregon	986,162	898,713	− 8.9
South Dakota	100,682	67,107	−33.3
Texas	586,120	798,917	+36.3
Utah	1,371,651	1,324,125	− 3.5
Washington	529,899	499,283	− 5.8
Wyoming	1,207,982	1,236,155	+ 2.3
Total for 19 states	19,191,716	19,547,544	+ 1.9

Limitations of water supply and costs of construction will determine the total area that may ultimately be irrigated. While the extent of future development cannot be forecast with definiteness, it is generally considered that available water supplies will limit irrigation to from 3 to 8 per cent of the gross area of these states.

Even in the more arid states, irrigation is not the only form of farming practiced. In the 19 states for which the census reports irrigation, only 7.8 per cent of the total number of farms were irrigated. The proportion of the farms irrigated varies from a negligible percentage in the semi-humid states to as high as 88 per cent in Nevada and Utah. In Idaho, Colorado, California, and Arizona about 60 per cent of the total number of farms are irrigated. The proportion of the value of crops from irrigated lands to the total value of crops grown in these states is much higher than the proportion of the area irrigated to the total cropped area.

CLIMATE AS AFFECTING IRRIGATION

Climate as expressed in terms of precipitation is usually divided into three general classes. These are (1) arid, (2) semi-arid, and (3) humid. The divisions between these classes are usually made on the basis of the mean annual precipitation, although other factors such as seasonal distribution of rainfall, temperature, humidity, and wind movement affect the usefulness to crops of any given amount of mean annual precipitation. Different writers have selected different amounts of rainfall for the divisions between these classes. The following basis represents typical values:

Class	Mean annual precipitation, inches	Remarks
1. Arid	Less than 15	Irrigation necessary
2. Semi-arid	15 to 30	Irrigation optional
3. Humid	Over 30	Irrigation sometimes beneficial

The line of 15 in. mean annual rainfall in the United States occurs generally along the eastern boundary of Montana, Wyoming, Colorado, and New Mexico. There are many areas west of this line which receive over 15 in. of rainfall but these are largely confined to the higher altitudes where farming lands are less extensive or are in those parts of the northern Pacific Coast where the occurrence of the rainfall during the winter season limits its usefulness to crops.

The line of 30 in. of mean annual rainfall passes through western Wisconsin, crosses Iowa, and runs south through eastern Kansas, Oklahoma, and Texas. East of this line the annual rainfall in the agricultural areas varies from 30 to 50 in.

Dry farming is practiced in many areas having less than 20 in. mean annual rainfall. However, such practice is usually replaced by irrigation wherever water supplies can be made available at reasonable costs. Owing to limitations in the available water supplies in the western states, most of the land will continue to be used for dry farming, grazing, or timber. Under favorable conditions dry farming may be practiced for cereal crops with mean

annual rainfalls of 12 in. but crop returns are widely variable and uncertain.

Causes of Rainfall.—When a mass of air is cooled sufficiently below the dew point at temperatures above 32° F., rain results. Minor cooling may form only fog or clouds. Cooling by expansion as air rises is the most effective cause of rainfall. Rising of air is caused by (1) being forced up the side of mountains into a region of lower temperature, such as where the prevailing winds are at right angles to a mountain range, (2) convectional currents or the overturning of the lower air due to its heating, (3) cyclonic storms where air flows into a region of low pressure, which causes the air in the center to rise. Convectional currents are the principal cause of summer thunderstorms. Cyclonic storms are more important in the eastern part of the United States than in the west.

The conditions that result in abundant rainfall are (1) nearness to the ocean, (2) location in the track of usual cyclonic storms, and (3) mountain ranges. These causes may operate singly or in combination. Condition (1) does not always apply, as in Southern California; condition (2) is less effective in the interior of continents where the vapor supply may be small. Montana is in the storm paths, but the rainfall is generally small as there is little remaining moisture to be precipitated. In the north Pacific Coast all three conditions occur.

Seasonal Distribution of Rainfall.—The distribution of rainfall throughout the year materially affects its usefulness in crop production. Where irrigation is not practiced, it is necessary that rains should occur in sufficient amount and frequency to maintain an adequate supply of available soil moisture for use by the crops. A single period of drought during the growing season may result in an entire loss of production of the crop. As the capacity of soils to absorb and retain moisture within the depths from which it may be utilized by the crop roots is less than the amount of moisture required for full crop production, sufficient moisture cannot be stored in the soil from rains occurring prior to seeding to produce adequate crop yields unless additional moisture is received during the period of crop growth. Winter rainfall is useful for summer growth only to the extent to which it can be retained in the soil within reach of the crop roots; winter precipitation in excess of such soil moisture storage capacity is not useful to the crops.

In the western part of the United States there are four general types of seasonal distribution of precipitation. These are generally called the Pacific, Intermountain, Great Plains, and Southwestern. Examples of these types are shown in Fig. 1 based on U. S. Weather Bureau records of precipitation.

The Pacific type of rainfall applies to the areas along the Pacific Coast and extends eastward to the Cascades and Sierra

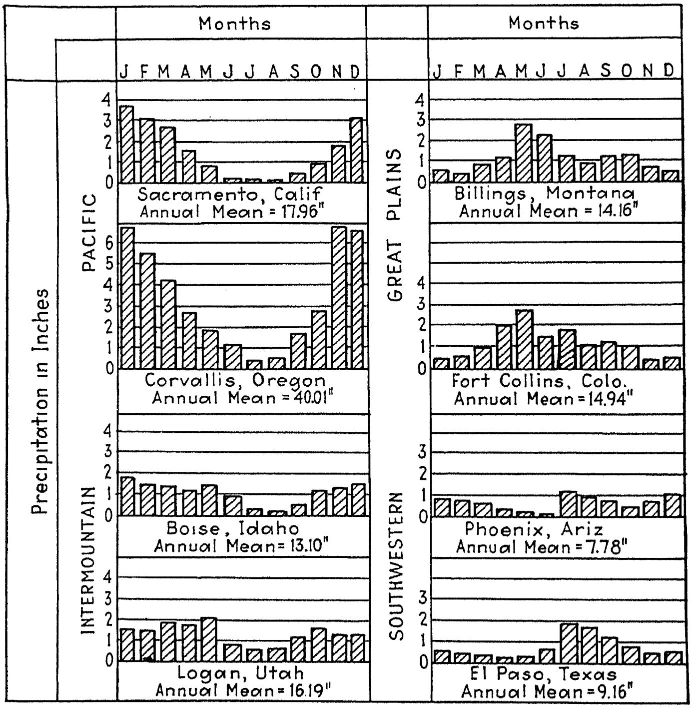


FIG. 1.—Monthly precipitation in inches at typical western stations illustrating amount and distribution of rainfall. (*From records of U. S. Weather Bureau.*)

Nevadas. In this type, the precipitation occurs mainly during the winter months, that during the summer being almost negligible in amount. It is illustrated by the records for Sacramento, Calif., and Corvallis, Ore., in Fig. 1. In general, the amount of the mean annual rainfall in this area increases from the south toward the north; for the agricultural areas, the annual mean varies from 15 in. in Southern California coastal areas, less than 10 in. in the southern portion of the San Joaquin Valley, 25 in. in the northern portion of the Sacramento Valley to over 50

in. in some of the coastal valleys of Oregon and Washington. While the Pacific type of seasonal distribution of rainfall is unfavorable to direct use by most crops, the winter precipitation which occurs largely in the form of snow on the higher drainage areas does not melt until the spring and early summer months when the resulting run-off is directly useful for irrigation. In many parts of the area, the winter temperatures are sufficiently high to permit the production of cereals by direct use of the rainfall. The winter precipitation also furnishes sufficient moisture for the early season growth of other crops and permits delaying the beginning of their irrigation.

The Intermountain type of precipitation applies to the areas between the Coast Ranges and the Rocky Mountains from Arizona north. It is illustrated by the records for Boise, Idaho, and Logan, Utah, in Fig. 1. The total annual amount is generally less than in the Pacific area but the distribution throughout the year is more uniform. The amount of rainfall during the spring months enables the beginning of irrigation to be delayed in those areas receiving 15 in. or over total annual rainfall. Dry farming of cereals is successfully practiced in some of the more favorable parts of this area. The total mean annual precipitation in the agricultural areas varies from less than 5 in. in some parts of the southern portion to 10 to 20 in. in the northern. Larger precipitation occurs on the higher mountainous areas.

The Great Plains type of rainfall applies to the arid and semiarid areas lying east of the Rocky Mountains and west of the more humid Mississippi Valley lands. In this area the largest monthly rainfalls occur in the early summer months when the moisture received is directly useful to crops. The amount of such early season rainfall is frequently sufficient to meet the crop requirements during their early stages of growth and irrigation may not be applied until the warmer portions of the summer season. A larger proportion of the mean annual precipitation is directly useful to crops in the Great Plains type than for the other western areas. The mean annual precipitation in most of this area varies from 10 to 20 in. It is less variable from south to north than in the Pacific and Intermountain areas. This type of precipitation is illustrated by Billings, Mont., and Fort Collins, Colo., in Fig. 1.

The Southwestern type of precipitation applies to Arizona and New Mexico and some adjacent areas. It is characterized by

larger rainfall in the late summer months. It represents an Intermountain type of rainfall with an addition of later summer storms. It is illustrated in Fig. 1 by the records for Phoenix, Ariz., and El Paso, Tex. The mean annual precipitation in the agricultural areas varies from almost nothing to 15 to 20 in., being generally larger in the areas of higher elevation. The individual summer storms are sufficiently heavy at times to aid in meeting the crop requirement both directly on the cropped lands and by providing run-off in the streams for diversion for irrigation.

For all of the four areas receiving these types of rainfall, the principal sources of water supply for irrigation are the run-off of the streams draining the higher mountainous areas. In all areas precipitation is larger at the higher elevations. On the higher areas, the snowfall represents a form of natural storage holding back the run-off until the period of crop use. In almost all of the valley areas the precipitation is inadequate to produce much run-off and the availability of a dependable water supply for irrigation is dependent mainly on the extent of higher drainage areas tributary to the valley agricultural lands.

Annual Variations in Rainfall.—The preceding discussion has related to the mean annual precipitation and its seasonal distribution. While the mean annual rainfall is a convenient basis on which to compare different areas, the usefulness of the rainfall in any given area depends on the uniformity of the precipitation as well as on its amount. The rainfall in any year may vary widely from the mean. In general, the variations are proportionately larger in areas of small rainfall. Areas having a sufficiently large mean annual rainfall for crop production without irrigation may find irrigation is required in years of less than normal rainfall. If such deficient years occur frequently, irrigation is usually provided for those lands for which a water supply can be made available at reasonable cost.

In the western areas the precipitation in minimum years may be less than one-half the long-time mean. Two consecutive years may average less than 60 per cent of the mean and three consecutive years may average less than 70 per cent of the mean. Ten-year periods may vary as much as 20 per cent from the long-time mean, and twenty-five year periods may vary 10 per cent from the mean. These variations increase the difficulty of providing an adequate water supply. In years of deficient rainfall

and increased crop demand for water, stream flow is also below normal.

Storage is required for full utilization of the run-off both to enable the annual run-off to be made available when needed for irrigation and to carry over excess run-off of above normal years to those of deficient supply.

CHAPTER II

PHYSICAL PROPERTIES OF SOILS

The availability to plants of the moisture supply of soils is dependent on the physical properties of the soils in which the plants grow. This statement applies to all agricultural practice whether based on irrigation or on rainfall alone. The soil acts as a storage reservoir for the moisture used by the plants. As neither rainfall nor irrigation occurs in accordance with the daily crop demands, to be useful the moisture received at times of rainfall or irrigation must be stored in the soil within reach of the plant roots. The moisture holding capacities of the different soil types control the amount of water that can be retained from a single application and this, with the rate at which moisture is used by the crop, controls the frequency of irrigation required.

Classification of Soils.—The more usual classifications of soils are based on the sizes of the soil particles. As soils consist of varying proportions of the different sizes of soil grains, such a system of classification requires fixing the different sizes of soil particles to be segregated and the proportions of these sizes for the different textures to be recognized. The system of classification used in the United States is that of the U. S. Bureau of Soils which recognizes seven separate sizes of soil particles as follows:[1]*

	Size, Millimeters
Fine gravel or very coarse sand	2.0 to 1.0
Coarse sand	1.0 to 0.5
Medium sand	0.5 to 0.25
Fine sand	0.25 to 0.1
Very fine sand	0.1 to 0.05
Silt	0.05 to 0.005
Clay	Less than 0.005

Material coarser than 2 mm. is excluded from the sample before the proportions of the smaller sizes are determined. Sands and gravel as these terms are used in connection with engineering

* Numbers refer to references at end of chapter

work, such as in designation of materials used in concrete, are of larger sizes of particles than the largest sizes recognized in soil classifications. The proportion of each size is determined by mechanical analysis. The results are expressed in the percentage of the total weight for each size.

As the proportion of the seven sizes of soil particles varies for every soil sample, it is necessary to use general descriptive terms to represent soils having various proportions of the different sizes. For such classifications the particles larger than silt and clay may be combined. The general terms used by the U. S. Bureau of Soils and their definitions in terms of sizes of soil grains for the 10 principal soil classes are as follows:

MECHANICAL COMPOSITION OF THE PRINCIPAL SOIL CLASSES[1]

Soil classes	Limits in the proportion of the soil separates in percentage of the total soil weight		
	Sand	Silt	Clay
Sand	80 to 100	0 to 20	0 to 20
Sandy loam	50 to 80	0 to 50	0 to 20
Silt loam	0 to 50	50 to 100	0 to 20
Loam	30 to 50	30 to 50	0 to 20
Silty clay loam	0 to 30	50 to 80	20 to 30
Sandy clay loam	50 to 80	0 to 30	20 to 30
Clay loam	20 to 50	20 to 50	20 to 30
Silty clay	0 to 20	50 to 70	30 to 50
Sandy clay	50 to 70	0 to 20	30 to 50
Clay	0 to 50	0 to 50	30 to 100

Other more general terms used to describe soils are those based on general texture, such as coarse or fine. Sandy soils are frequently spoken of as "light" owing to the ease of cultivation, loams as "medium," and clay soils as "heavy" owing to the difficulty in handling clays when wet, although clay soils have a less weight per cubic foot than sandy soils. Other special terms include blow sands for soils having insufficient binding material to prevent movement under wind action and adobe or gumbo for clay soils that shrink and crack when dry and swell when wet.

The more finely divided clay particles are called "colloids." The proportion of colloids materially affects the soil-moisture properties of soils. Colloids absorb moisture and soils containing

a relatively large proportion of its clay in colloidal form have a greater soil-moisture capacity and a slower rate of soil-moisture movement than ordinary clays.

The preceding classifications are based entirely on the mineral materials of soils. Soils also contain decomposed organic material known as "humus." Humus is one of the essential elements of soil fertility and its amount affects to some extent the moisture holding capacity of the soil. Humus in ordinary soils does not exceed a few per cent of the soil weight. Muck and peat are soils in which the organic material varies from 20 to 90 per cent of the soil weight. Such soils are formed from the decomposition of plants in bogs and marshes; muck represents soils in which the decomposition of the organic material is more complete than in peat.

Pore Space.—All soils contain pore spaces between the soil grains. If all soil particles were spheres of uniform diameter, the pore space would be independent of the size of the spheres and would vary from 26 per cent of the volume when packed as closely as possible to 48 per cent when arranged with their centers in squares. As the soil grains are neither spherical nor of uniform size, the pore space varies more widely. Small soil particles when mixed with those of larger size may reduce the pore space when they occupy the voids between the larger grains; the small particles may increase the pore space if they hold the larger grains apart.

The proportion of the pore space to the total soil volume varies with the texture of the soil, being larger in soils having a large percentage of silt and clay. Sandy soils have larger individual spaces between the soil grains but the total number of pore spaces and the total percentage by volume of the pore spaces are smaller than for fine-textured soils. Under field conditions the pore space of most cultivated soils varies from 35 to 50 per cent of the soil volume. For sandy soils the pore space may be as low as 20 per cent; for some clay soils the pore space may exceed 50 per cent of the soil volume.

Soil Weights.—The weights of soils vary with the pore space. The specific gravity of the mineral matter of the soil is usually from 2.50 to 2.70. With the usual percentage of pore space the apparent specific gravity varies from 1.25 to 1.75. Usual oven-dry weights per cubic foot are for clay soils 75 to 80 lb., loams 85 to 90 lb., sandy loams 90 to 95 lb., and sands 95 to 105 lb.

Variations in Soil Texture.—Much variation occurs in soils both vertically and horizontally. Alluvial soils may vary widely in texture within the same field area. Vertical variations are frequent in arid soils. Such variations may be desirable or harmful depending on their effect on the moisture holding capacity of the soil.

Many arid soils contain subsoils of a more or less impervious character which obstruct the penetration of water and plant roots. Such subsoils are frequently called "hardpan." The term hardpan is applied to any indurated or impervious subsoil layer and includes material varying from cemented rock strata to compact clays. Hardpan usually occurs in layers underlaid by soil. Some hardpans are continuous and are impervious to water and roots; others are merely more slowly pervious than the overlying soil. Heavier subsoils may be of benefit in coarse soils if at a depth below the surface large enough to permit proper root development, as they retard downward moisture movement and increase the moisture holding capacity of the surface soil; care is required however to avoid the collection of excess moisture in the soil on top of the hardpan.

Some subsoils consist of coarse sand or gravel having only limited moisture holding capacity. Such subsoils, if at sufficient depths, are an advantage in providing drainage for heavy surface soils. For sandy surface soils in which the moisture capacity is inadequate because of insufficient depth of soil, such subsoils make necessary more frequent irrigations.

In some of the irrigated areas of steeper slopes, the soil may be formed by the disintegration of the rock material in place. These are called "residual soils"; their depth varies with the age and character of the rock and with the climatic conditions. Residual soils are frequently shallow.

SOIL-MOISTURE TERMS

The amount of soil moisture may be expressed in terms of weight or of volume. Both forms of expression are needed and used. Moisture in terms of weight is expressed as the percentage of the weight of moisture to the oven dry weight of soil. Moisture in terms of volume may be expressed either in percentage of the total volume of soil or in the equivalent depth in inches of water per foot depth of soil. The latter term is useful in comparing the amounts of soil moisture with the depths of rainfall or

gation, as such depths are usually expressed in inches or feet ›th of water over the area.

›oil samples for moisture determinations are usually taken h an auger or tube. Where distribution of moisture is to be ermined, the sample for each foot of soil depth is kept separate. or a representative part of the sample is dried in an oven at ıperatures at or above 100° C. until no further loss of weight urs. The difference in weight of the sample before and after ing represents the water evaporated from the sample. This erence divided by the weight of the sample after drying gives percentage of moisture by weight of the dry soil.

›oil moisture in terms of percentage by weight may be conted to percentage by volume if the dry weight per cubic foot he soil is known. To compute the moisture in terms of depth vater, the weight of water may be taken as 62.5 lb. per cubic t. Though the actual weight of water varies slightly with its ıperature and purity, the above value is sufficiently accurate soil-moisture determinations.

Conversions may be made by the use of the following formula:

V_m = percentage of moisture by volume.
W_m = percentage of moisture by weight of dry soil.
W = dry weight of soil, pounds per cubic foot.
62.5 = weight of 1 cu. ft. of water, pounds.
$\times$ 62.5 = pounds of moisture per cubic foot of soil.
$_m \times W$ = pounds of moisture per cubic foot of soil.

ərefore

$$V_m = \frac{W_m \times W}{62.5},$$

can be converted to depth of water in inches per foot depth oil by multiplying by 0.12.

$$W_m = \frac{V_m \times 62.5}{W}.$$

FORMS OF SOIL MOISTURE

'he form in which moisture is distributed and held in soils es with the amount of moisture present. The smaller ›unts of moisture are held as a capillary film surrounding the grains. The smaller the amount of moisture, the more tly is the moisture film held by the soil particles. As the

amount of moisture increases, the surface tension of the moisture film decreases and moisture moves more freely in the soil and is more easily obtained by plant roots. Larger amounts of moisture fill the pore spaces in the soil and have little surface tension as moisture films. Such moisture moves relatively freely in the soil under the influence of gravity. Several different classes or amounts of soil moisture are recognized as an aid in classifying the soil moisture in relation to its availability for plant use. The more usual terms and their definitions are as follows.

Soil Saturation.—When all the pore space of a soil is filled with water, the soil is spoken of as "saturated." Soil below the depth of the ground water is saturated. A condition of temporary saturation may occur at and immediately following an irrigation. The amount of moisture contained in a saturated soil in terms of volume is equal to the percentage by volume represented by the pore space and in terms of weight to the percentage by weight resulting from the weight of water in the pore space and the dry weight per cubic foot of the soil.

Soils free to drain will not retain sufficient water to cause saturation. Water in excess of that held in capillary form by the soil grains will move downward under the action of gravity. Permanent saturation occurs in soils only where drainage is prevented by impervious soil strata or by lack of outlet for water applied in excess of the ability of the soil to retain moisture in the form of films surrounding the soil grains.

Capillary Capacity.—The moisture soils can retain against the action of gravity when free to drain is called the "capillary capacity" of the soil. For field conditions the terms "field capillary capacity," "field capacity," or "specific retention" are frequently used. The capillary capacity represents the amount of moisture for which the surface tension of the moisture film exceeds the force of gravity. The amount of the field capacity varies with the soil texture. From 40 to 60 per cent of the pore space of the soil is filled with moisture at the field capacity. General values of the field capacity in terms of percentage by weight are 8 to 15 for sandy soils, 15 to 20 for medium soils, and 20 to 25 for heavy soils.

Moisture Equivalent.—The moisture equivalent is an artificial moisture property of soils used as an index of the natural properties. It represents the moisture retained by a soil when subjected to a force of one thousand times gravity in a centrifugal apparatus

using specified sizes of soil samples. As the textures of soils vary widely, it is difficult to express the moisture properties of the soil by any one factor. The moisture equivalent has been used as a single unit to which other moisture properties can be related. For soils of medium texture the moisture equivalent is frequently approximately equal numerically to the field capacity; for coarse soils the moisture equivalent is less than the field capacity; for fine-textured soils the moisture equivalent is generally greater than the field capacity.

Minimum Moisture Desirable.—As the soil moisture supply approaches the minimum moisture content at which moisture is obtainable by the plant roots, plants secure moisture with increasing difficulty. In order that the crop may not be injured by moisture shortage, it is desirable that water should be supplied before the rate of growth is affected. The point at which it is good practice to replenish the soil-moisture supply may be called the minimum moisture desirable. Some available moisture remains in the soil at the time irrigation becomes advisable. Several days may be required to apply water to fields and irrigation must be started so as to be completed before injury occurs.

The surface soil is frequently dried below the point of usefulness to the plants, the crops obtaining their moisture at such times from the deeper soil. Deeper-rooted crops such as orchards can be permitted to reduce the soil moisture in the upper few feet of soil below the point that is desirable with more shallow-rooted crops. The minimum moisture desirable represents the moisture condition in the depth of soil from which the crops obtain their moisture supply when irrigation is advisable.

Wilting Percentages.—A shortage in moisture is shown by plants first by drooping followed by wilting. Plants may droop during the hotter portions of the day even if adequate moisture is available in the soil if the rate of use of moisture by the plant exceeds the rate at which the roots can absorb and transmit moisture to the leaves. When the plants do not recover in the periods of reduced transpiration at night and wilt to a point where water must be added to the soil to restore the turgidity of the plant, the soil-moisture content is called the "wilting percentage" or the "wilting coefficient." This is a lower moisture content than should be permitted to occur if water supplies are available for its prevention. At the wilting coeffi-

cient, the force with which the soil grains hold the moisture film exceeds the force the plant roots can exert in extracting moisture from the soil.

The soil moisture may be reduced below the wilting percentage under field conditions. The surface soil may be reduced by air drying. Part of the deeper soil may also be reduced below the wilting percentage if there is available moisture in other parts of the soil mass within reach of the plant roots. Plants may obtain some moisture below the wilting percentage but the rate at which it is obtained is insufficient to maintain plant growth unless other sources of moisture supply are also available.

Where plants were grown in pots so that the soil moisture of the entire soil volume was reduced relatively uniformly, observations in Colorado[2] showed wilting percentages by weight of less than 1 per cent for coarse sand, 2.5 to 3.5 per cent for fine sand, 5 to 6 per cent for sandy loam, 10 to 15 per cent for loam, and 14 to 16.5 per cent for clay loam. No essential difference occurred in the wilting percentages for different crops.

Under field conditions, the soil moisture is not uniform at the time of wilting. Wilting occurs whenever the total moisture obtainable by the plant from all of the soil on which the roots are drawing is insufficient to maintain growth. The soil moisture may vary from less than the wilting percentage at the surface to saturation below the depth of root growth.

Hygroscopic Moisture.—Soils exposed to the air will have their moisture content reduced below the wilting percentage. The moisture the soil is able to retain when air-dried or the moisture an oven-dry soil will absorb from saturated air at a constant temperature is called the "hygroscopic moisture" or "hygroscopic coefficient." While not useful to plants, hygroscopic moisture must be present in soils before the soil can contain the useful portions of the soil moisture.

The hygroscopic moisture in percentage by weight varies from as low as 2 per cent for fine sands to as high as 15 per cent for heavy clays. Where plants are grown in tanks so that all of the soil has its moisture content uniformly reduced, the hygroscopic moisture has been found to be equal to about two-thirds of the wilting percentage.[2] Under field conditions where plants may obtain some moisture from deeper soil, the moisture in the upper soil may approach more nearly to the hygroscopic moisture before actual wilting occurs.

RELATIONSHIPS OF MOISTURE PROPERTIES OF SOILS

The soil moisture readily available to plants is represented by the difference between the field capacity and the moisture when irrigation is desirable. Plant roots require air as well as water in the soil. Saturated soils lack air; dry soils contain adequate air but lack moisture. There is no single optimum proportion between air and water in soils. Crops grow to equal advantage with the moisture anywhere between the minimum desirable

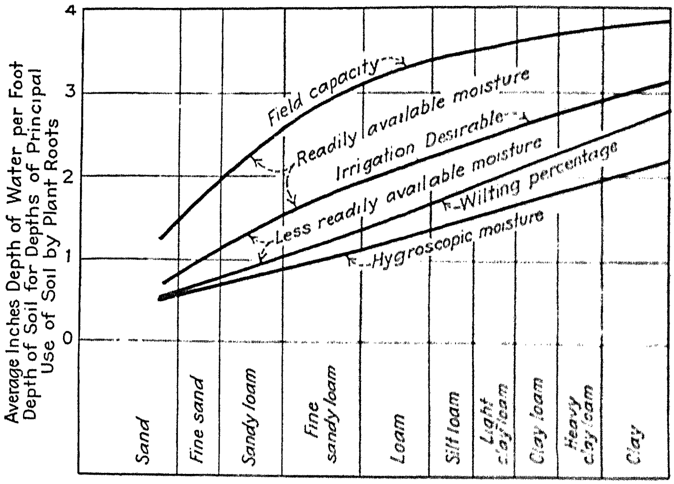


FIG. 2.—Generalized relation of principal soil-moisture properties.

and the field capacity. A soil free to drain will not retain sufficient water to be harmful to the crops. The rate of growth is not reduced owing to shortage of moisture until the supply begins to approach the wilting percentage.

Soil moisture is continually changing. On bare soils adjustments take place following rain or irrigation, moisture moving downward by gravity flow or capillary movement as capillary adjustment takes place and upward by capillary movement as evaporation from the soil surface occurs. On cropped lands similar adjustments take place, complicated in addition by the extraction of moisture by plant roots. Moisture in soils under field conditions is never uniform or stable, although it may approach stability at the lower moisture contents. Consequently observations under field conditions which represent the moisture

content at the different moisture points are difficult to obtain.

Generalized relationships of the four principal soil-moisture properties are shown in Fig. 2, in which the average inches depth of water per foot depth of soil for the usual depths of soil moisture use by crops are plotted in relation to the soil texture. The curves in Fig. 2 represent the moisture content that would be expected if the soil moisture to the depth of principal plant use was uniform. For usual conditions the soil moisture in the surface foot of soil is larger at field capacity and smaller when irrigation is desirable than the average for the depth of soil from which the crops secure their principal supply.

Figure 2 illustrates the proportion of the total soil moisture that may be useful to plants and the large differences in the amounts of moisture in soils of different textures. The hygroscopic moisture for heavy soils exceeds the field capacity of coarse-textured soils. While a larger percentage of the field capacity is available to plants in coarse soils than in those of heavier texture, the actual amount of readily available moisture is less than that for heavier soils.

For light-textured soils without heavier subsoils, or where ground water does not occur within reach of the crop roots, an average of from 0.5- to 0.75-in. depth of water per foot depth of soil for the usual depths of soil utilized by the crop can be added and retained from an irrigation. Moisture movement occurs readily in such soils and the amounts of moisture shown for the field capacity in Fig. 2 can be obtained to the full depth of penetration desired. As general crops may utilize moisture to depths of 5 or 6 ft., 3- to 5-in. depth of water may be added and retained in such soils from an irrigation. Sandy soils with heavier subsoils may retain larger amounts of moisture.

For uniform soils of medium texture, from 1- to 1.25-in. depth of water may be added and retained per foot depth of soil where the soil is free from heavy subsoils or the effects of the ground water table. As penetration is also readily secured in such soils, 6-in. total depth of water may be added to the soil moisture and retained within reach of the plant roots.

For heavy soils the field capacity shown in Fig. 2 may be exceeded if absorption to the full depth of usual plant roots can be obtained without having water on the land so long that crop

injury results. For very heavy soils, penetration of moisture may be obtainable only to depths of 1 to 3 ft., thus limiting the total moisture storage that may be secured from an irrigation. For such heavy soils the actual moisture capacity is larger than that for soils of lighter texture but the inability to secure penetration to the full depths desired reduces the average amount of readily available moisture below that for medium-textured soils. For heavy soils the average depth of water that may be absorbed and retained in the upper 3 to 6 ft. of soil varies from 0.75 to 1 in. per foot depth of soil with totals per irrigation of from 4 to 6 in. on clay loams to as small as 2- or 3-in. depth of irrigation on heavy clays.

Where soils are permitted to approach the wilting percentage, larger amounts of moisture may be added and retained. Larger depths per irrigation may also be retained within reach of deep-rooted perennial crops owing to the greater depth of soil utilized. Where irrigations are applied when surface soils have become dry before the moisture below 3-ft. depth has been used, the average amounts added and retained from an irrigation are less than the amounts stated above for uniform use of soil moisture. This condition obtains for much practice with annual crops or for perennial crops having the larger part of their feeding roots in the surface soil.

For all soils in which the depth from the surface to the water table is so small that the lower portion of the soil depth containing the root system derives a substantial part of its moisture from the capillary rise of subsoil water, the irrigation water which may be retained from a single irrigation may be considerably less than those indicated above.

MOVEMENT OF SOIL MOISTURE

The principal moisture supply for plants is secured between moisture contents represented by the field capacity and the minimum desirable. Such soil moisture occurs in capillary form and is subject to capillary forces in its movement. Capillary moisture tends to move from the more moist to the less moist soil so as to equalize the surface tension of the moisture film. While the forces tending to cause capillary movement of soil moisture are definite and positive, the quantity of movement in relation to the moisture requirements of plants is of larger

practical importance than the principles controlling capillary action.

Movement of capillary moisture may occur in all directions. Downward movement of rain or irrigation after the distribution of water in excess of the field capacity occurs as capillary flow. Lateral distribution in furrow irrigation is largely by capillary movement. Moisture moves upward into the soil above the water table by capillary action.

Where marked variations in soil texture occur, capillary movement is largely stopped. Moisture will not move from a soil into a gravelly subsoil until more moisture has collected in the soil just above the coarse material than would be required for downward capillary movement in a uniform soil.

As moisture is removed by the plant roots from the soil with which they are in contact, capillary action tends to cause moisture to move toward the roots from the adjacent soil. For usual amounts of soil moisture the amount of such movement is small and the moisture obtainable by the plants from such capillary action is less than the moisture needed to maintain plant growth. For such soil-moisture conditions, plants obtain their moisture supply by extending their roots into the soil containing moisture rather than by capillary movement to the roots, such capillary movement being effective in soils of small moisture content for only very short distances. Where a source of water supply is continuously available, such as where the roots reach into soil within the height of capillary rise above the water table, capillary movement to the soil surrounding the roots may supply an important part of the crop needs.

CAPILLARY MOVEMENT INTO DRY SOILS

If a column of dry soil is placed in contact with water at its lower end, moisture will rise into the soil column by capillary action until the capillary forces are in equilibrium. The rate of rise and the total height of rise vary with the soil texture. The initial rate of rise is more rapid in the soils of coarser texture but the greatest total height of rise occurs in soils of heavier texture. This is illustrated by the results shown in Fig. 3. The initial rise was more rapid in the coarser soils but the largest total rise occurred in the lava ash soil. While the curves in Fig. 3 show

some rise to the end of the period of observation, the maximum height of rise had been nearly reached in the 30 to 60 days shown.

The effect of the direction of movement on the distance capillary moisture will move into dry soil is shown in Fig. 4. The box sloping up at 45 deg. and the vertical box were enclosed on four sides so that the soil was not exposed to evaporation. In the other flumes one side was open so that some soil-moisture evaporation occurred. The much more rapid capillary movement where aided by gravity than where opposed is evident from these results.

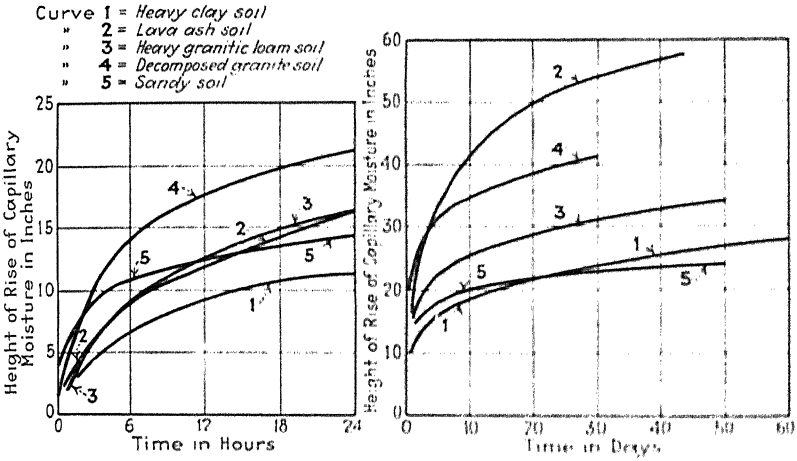


FIG. 3.—Rate of rise of capillary moisture in vertical columns of dry soil. (*Adapted from McLaughlin.*[3])

Capillary moisture is not uniformly distributed in a soil above a source of moisture supply. The largest amount of moisture occurs a short distance above the water surface. The moisture gradually diminishes to the point of maximum height of rise. This is illustrated by the results shown in Fig. 5 giving the distribution of moisture in 1½-in. square vertical soil columns for different types of soil.[4]

The capillary rise of moisture is affected somewhat by the size of the soil column. Laboratory experiments in which square columns of dry fine sandy loam soil were placed in contact with a free water surface on their lower end showed the following heights of capillary rise over a period of 263 days:[5]

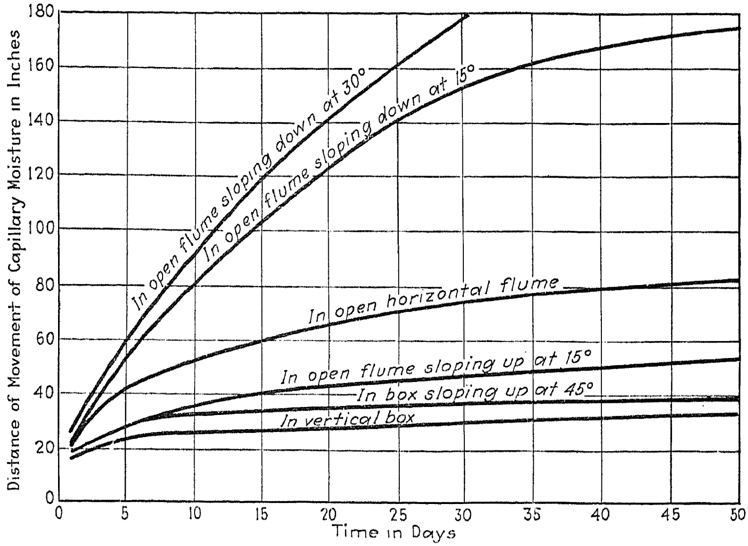


FIG. 4.—Rate of movement of capillary moisture into dry heavy loam soil on various slopes. (*Adapted from McLaughlin.*[3])

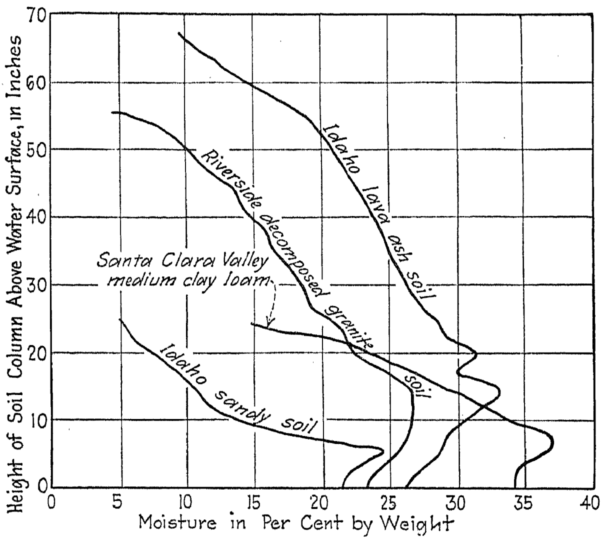


FIG. 5.—Distribution of capillary moisture in vertical soil columns. (*Adapted from McLaughlin.*[4])

Size of Column, Inches	Capillary Rise, Inches
1	33.6
2	46.5
3	53.6
4	53.7
5	55.7
6	56.5
8	56.4
12	58.0

MOVEMENT OF CAPILLARY MOISTURE UNDER IRRIGATION PRACTICE

When water is applied to the surface of a soil, the moisture absorbed distributes itself under the combined action of gravity and capillarity. Except for the initial movement at the time of application when the upper soil may be saturated, such movement is mainly by capillary action. The rate of such capillary movement depends upon the moisture content of the soil, being much slower in relatively dry soils. For heavy soils which crack when dry, entry of water into the soil is mainly through such cracks rather than by general absorption through the surface soil. Downward capillary and gravity movements are also aided by the small passageways left by roots and wormholes.

Movement of moisture in an uncultivated and uncropped sandy loam soil following an irrigation of 4.5-in. depth is shown by the results of observations in the Yakima Valley in Washington in Table I.[6]

TABLE I.—AVERAGE MOISTURE CONTENT IN SIX PLATS IN INCHES DEPTH OF WATER PER FOOT DEPTH OF SOIL AT PROSSER EXPERIMENT FARM[6]
July and August, 1924

Soil depth, feet	One day before irrigation	One day after irrigation	Three weeks after irrigation	Six weeks after irrigation
1	0.46	2.89	1.48	1.39
2	0.78	2.23	1.76	1.63
3	0.96	1.16	1.43	1.33
4	1.18	1.21	1.33	1.27
Total..........	3.38	7.49	6.00	5.62

The samples one day after irrigation showed an increase in moisture nearly equal to the depth applied. A small amount

of penetration to a depth of 4 ft. had occurred, although the soil through which the moisture passed was not raised to the field capacity. The moisture before irrigation represents about the wilting percentage for this soil. The changes in moisture 3 and 6 weeks after the irrigation represent the combined effects of drying of the upper soil by evaporation and downward capillary movement into the third and fourth feet of depth.

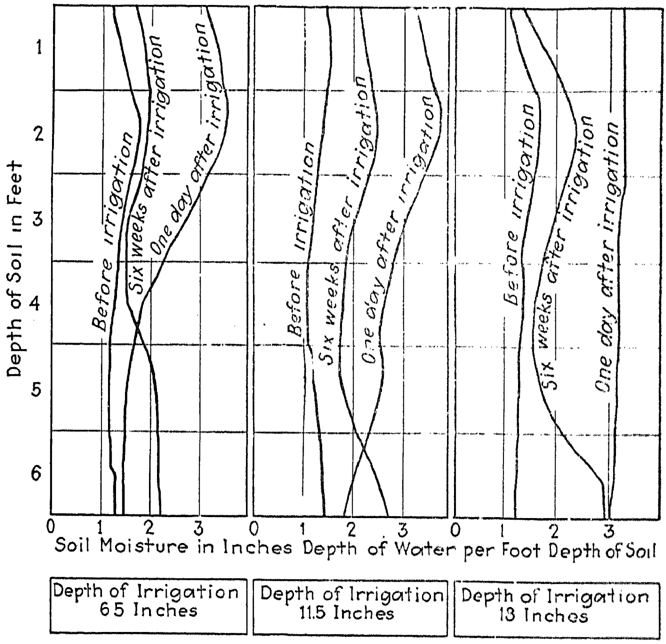


FIG. 6.—Changes in soil moisture on bare sandy loam soil with different depths of irrigation at Prosser Experiment Farm in Washington. (*Adapted from Scofield and Wright.*[6])

Figure 6 shows the results of observations on soil-moisture distribution from irrigations of different depths for the same bare sandy loam soil represented in Table I.[6] The soil before irrigation was above the wilting percentage and at the moisture content at which irrigation for crops would be desirable. All depths of irrigation raised the surface soil to field capacity. The 6.5-in. irrigation just penetrated to 6 ft.; some of the 11.5-in. irrigation passed below 6 ft. although the upper soil was not all raised to field capacity, and the 18-in. irrigation brought the entire 6-ft. depth to field capacity. The increase in moisture in the

upper 6 ft. of soil one day after irrigation accounted for 6.2, 9.9, and 11.0 in., respectively, of the water applied. For the next 6 weeks, evaporation from the surface and downward capillary movement continued. For the 6.5-in. irrigation moisture moved down into the fifth and sixth foot from the third and fourth foot and upward for evaporation from the first and second foot. Similar movement occurred in the two other depths of irrigation. The total losses from the 6 ft. of soil in the 6 weeks after irrigation were 3.4, 4.5, and 7.0 in., respectively, the larger part of such loss being downward capillary movement into soil below the 6-ft. depth. As this land was uncropped, evaporation and downward movement were not affected by moisture use by roots during the period of these observations.

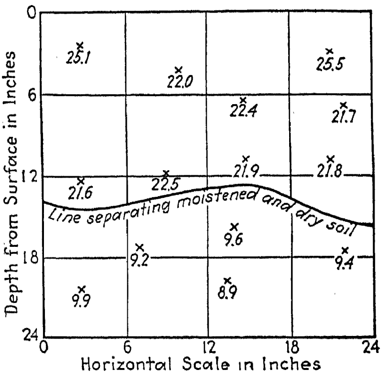


FIG. 7.—Penetration of rainfall into a dry loam soil at wilting percentage. Figures show percentage by weight of moisture 48 hr. after a rain of 2.15 in. (*Veihmeyer.*[7])

The slow movement of moisture into dry soil is illustrated by Fig. 7, based on moisture samples taken 48 hr. after a rain of 2.15 in. on a loam soil at Davis, Calif.[7] The soil was at the wilting coefficient prior to the rain; the rain filled the soil to the field capacity for a depth of about 14 in., leaving a sharp line between the moistened soil and the dry subsoil. While further distribution of moisture would occur, the rate of movement into the very dry subsoil would be very slow.

Movement of Moisture in Furrow Irrigation.—In furrow irrigation only a part of the soil may become moistened. Lateral penetration may not be sufficient to result in the moisture's meeting between the furrows. Downward penetration is dependent on the soil texture and the amount of water applied. In coarse soils downward movement may be so rapid that little lateral movement occurs. Best results in moisture distribution from furrows are usually obtained in the medium to medium-heavy soils, in which adequate absorption can be secured and in which fairly good lateral movement occurs before downward drainage is completed. On very heavy soils it is difficult to

secure sufficient absorption for adequate penetration either vertically or laterally.

Figure 8 shows the distribution of water from furrows on a fine sandy loam soil at Grandview, Wash.[8] Quite complete penetration both laterally and downward is shown. This soil has a more active capillary movement than some other soils of similar mechanical analysis. The moisture distribution is more complete than that obtained in much irrigation practice.

An illustration of movement of moisture from furrows is shown in Fig. 9. The observations were made on a sandy loam soil

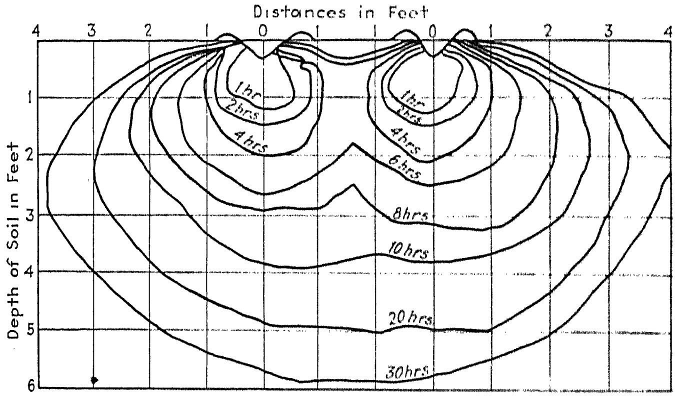


FIG. 8.—Distribution of moisture from furrows in sandy loam soil at Grandview, Washington. (*Sievers and Schafer.*[8])

underlaid with a sand. A trench was excavated across 16 furrows at the mid-point of their length of 660 ft. The water took 5 hr. to reach the trench and 17 hr. to reach the end of the furrows. The results shown were obtained by marking on the face of the trench the extent to which moisture had moved for the different times indicated. This irrigation did not moisten all of the soil. Only about 75 per cent of the top 3 ft. of soil was moistened with 40 per cent in the fourth foot, 28 per cent in the fifth foot, and 5 per cent in the sixth foot. Four furrows per tree row were used, made in pairs about 3½ ft. apart. Moisture had met in all cases between each pair of furrows but did not meet in the wider spaces between the pairs.

SEASONAL VARIATION OF SOIL MOISTURE UNDER IRRIGATION

Under usual conditions of irrigation practice the soil moisture is allowed to reach the minimum moisture desirable before an

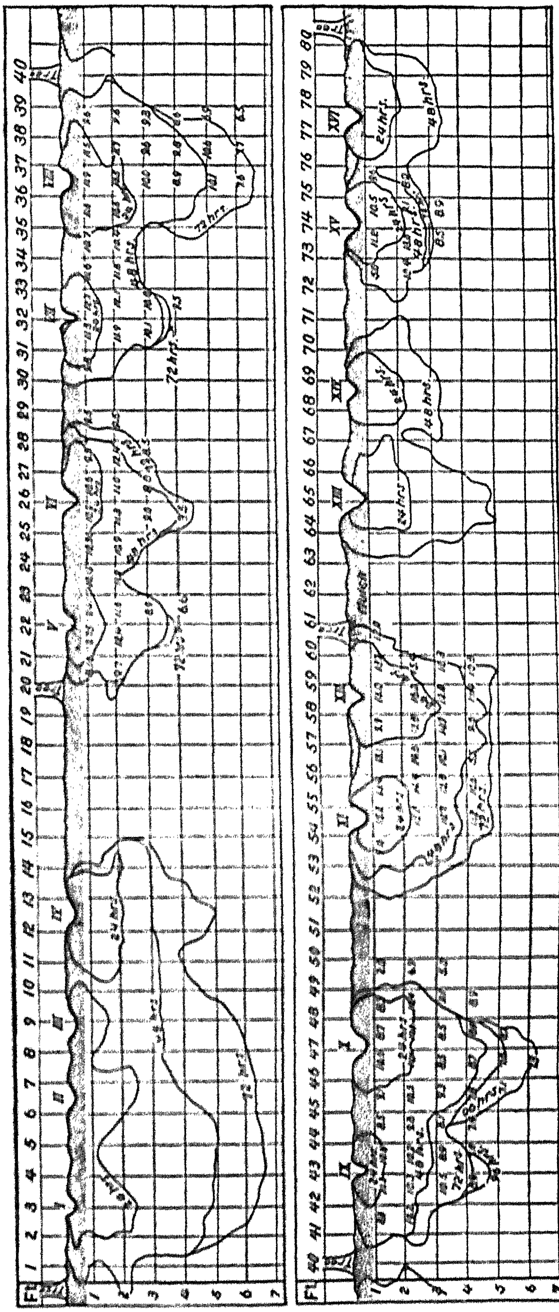


FIG. 9.—Outline of percolation under 16 furrows in sandy loam. (*Loughridge.*[3])

irrigation is applied. The depth of irrigation applied is then usually sufficient to raise the soil moisture to the field capacity to the depth of principal use of moisture by the crop. This practice results in the fluctuation of soil moisture between the field capacity and the minimum desirable, being increased quickly at the time of irrigation and diminishing gradually as the moisture is used by the crop until the next irrigation is applied.

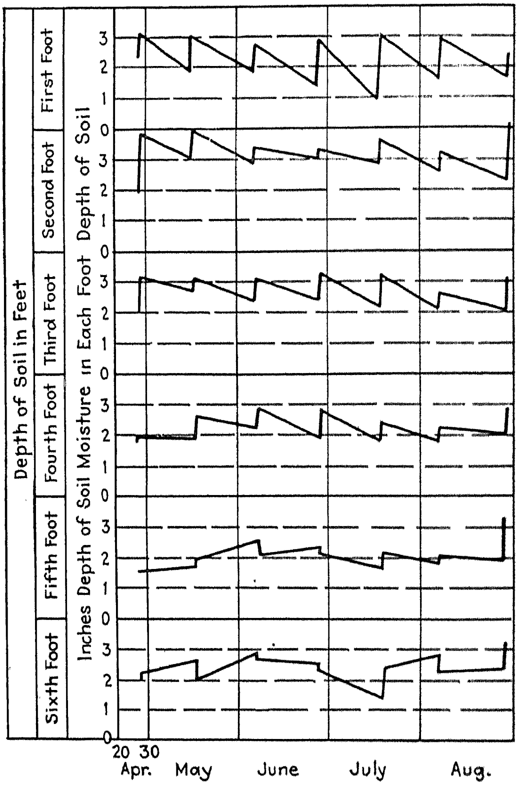


Fig. 10.—Fluctuations in soil moisture in each foot of soil to 6-ft. depth on sandy loam soil growing corn at Prosser Experiment Farm, Washington. (*Adapted from Scofield and Wright.*[6])

The seasonal fluctuations of soil moisture in each of the upper 6 ft. of sandy loam soil growing corn in 1926 on the Prosser Experiment Farm are shown in Fig. 10. Seven irrigations of 5-in. depth were used. An average of 3.87-in. increase in soil moisture was shown for each irrigation, the remainder of the depth of application evaporating from the soil or penetrating below 6 ft.

In addition to the irrigation, the rainfall from May to August was 2.32 in. An increase in moisture in each of the upper 4 ft. of soil occurred from all irrigations. In the fifth and sixth foot some decreases in moisture after irrigation were found where the soil was fairly moist before irrigation. Similar reductions in moisture have been found in other observations and have been considered to be caused by the downward movement of moisture at such depths due to the increased air pressure in the soil during irrigation caused by the inflow of water at the surface.

The seasonal variation of moisture in each of the upper 5 ft. of a sandy loam soil in a citrus orchard in San Diego County is

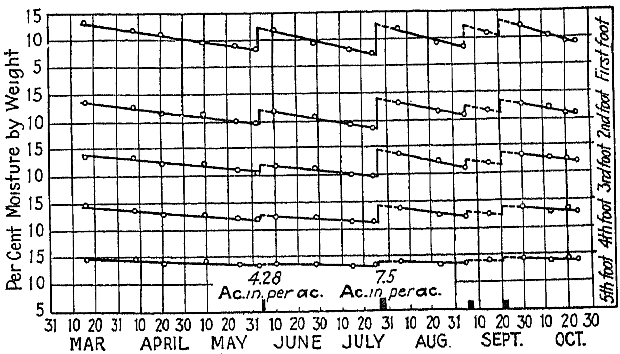


FIG. 11.—Seasonal variation in moisture content in citrus orchard. (*Beckett, Blaney, and Taylor.*[10])

shown in Fig. 11. Some penetration to 5 ft. is shown, but the larger part of the water applied was held in the upper 3 ft. of soil. A relatively uniform rate of moisture use between irrigations is shown. This soil has a field capacity of about 12.5 per cent by weight and a wilting percentage of about 7 per cent. Only the surface soil reached the wilting percentage; moisture was continuously available in the lower depths.

DEPTH TO WHICH PLANTS USE SOIL MOISTURE

The depth to which plants use moisture varies with the type of the plant and the soil. Annual crops usually extend their root systems to depths of from 4 to 6 ft. Many perennial crops extend their roots to greater depths. Roots of alfalfa have been found at depths of 40 or 50 ft. However, under usual irrigation practice the main mass of the smaller feeding roots occur in the

upper few feet of soil and the plants extract their moisture supply mainly from the upper soil.

Figure 12 shows the distribution of roots found in the Imperial Valley under various soil conditions. While the deep roots of alfalfa may be able to secure sufficient moisture to preserve the life of the plant during periods of moisture deficiency in the upper soil, such deeper moisture is inadequate for normal crop growth. As the rainfall in this area is negligible in amount, the

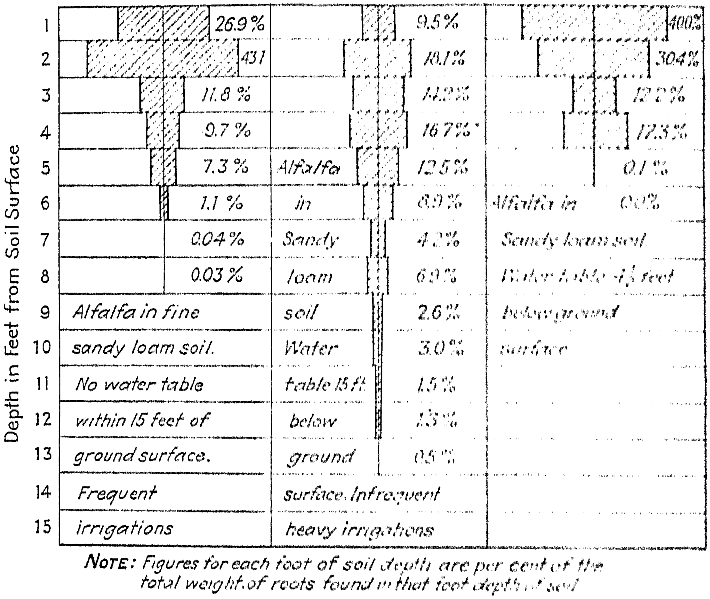


FIG. 12.—Distribution of feeding roots of alfalfa in Imperial Valley, California. (*Packard.*[11])

crops are dependent entirely on the moisture obtained from irrigation.

The effect of variations in irrigation practice on the distribution of the feeding roots of alfalfa was measured at Davis, Calif.[12] The resulting percentages of the total weight of roots in each of the upper 6 ft. of soil are shown in Table II.

No essential differences in root distribution are shown by these records. The normal rainfall at Davis is sufficient to cause moisture penetration during the winter months to a depth of over 6 ft., so that moisture is available in the spring for the full depth shown under all variations in irrigation.

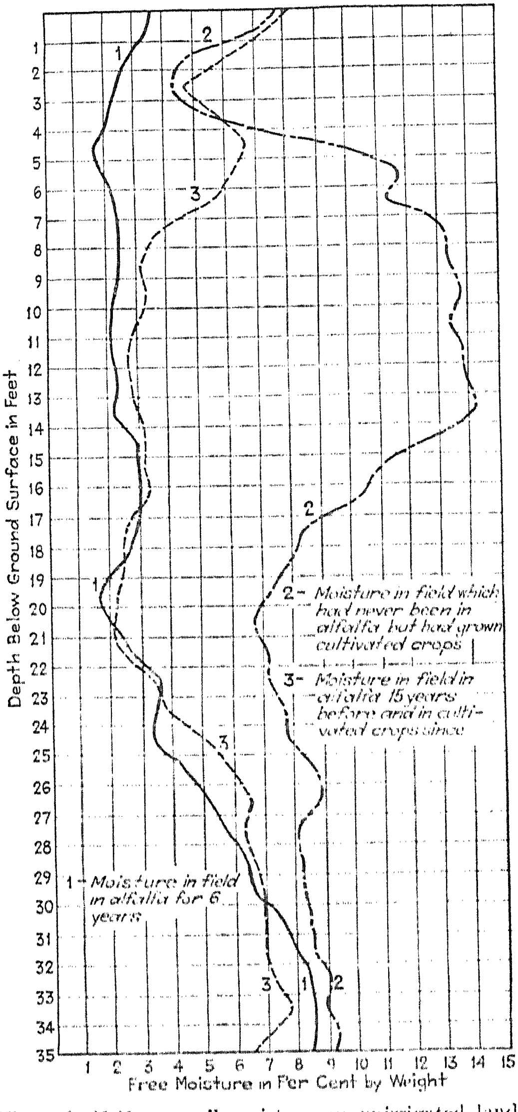


FIG. 13.—Effect of alfalfa on soil moisture on unirrigated land in Nebraska. (*Kiesselbach, Russel, and Anderson.*[13])

TABLE II.—DISTRIBUTION OF ALFALFA ROOTS AT DAVIS, CALIF., WITH DIFFERENT IRRIGATION PRACTICE IN PERCENTAGE OF TOTAL WEIGHT OF ROOTS FOUND IN EACH FOOT DEPTH OF SOIL[12]

Depth, feet	Twelve 2½-in. irrigations	Eight 3¾-in. irrigations	Six 5-in. irrigations	Four 7½-in. irrigations	Three 10-in. irrigations	Two 15-in. irrigations	Mean
1	47.2	57.5	53.1	47.8	52.5	51.3	51.6
2	20.4	18.2	19.4	19.4	18.9	20.0	19.4
3	13.8	10.1	11.7	12.4	12.2	9.3	11.6
4	8.7	6.2	7.4	8.7	7.1	8.0	7.7
5	5.8	4.7	4.9	6.6	5.5	6.4	5.6
6	4.0	3.3	3.5	5.1	3.8	5.0	4.1

The depth to which alfalfa may utilize the soil moisture is illustrated in Fig. 13 based on observations in Nebraska.[13] On lands which had grown alfalfa, a reduction in soil moisture to a depth of 35 ft. was found. The annual crops reduced the moisture in the upper 6 or 7 ft. of soil. Under the rainfall conditions in this area little penetration of moisture past the roots of annual crops occurs and there had been little recovery of the soil moisture used from lower depths by the alfalfa in the 15 years since it had been grown on the field represented by Curve 3.

The depth of rooting of trees varies. Citrus trees are in general more shallow rooted than deciduous trees and are mainly dependent on the moisture in the upper 5 or 6 ft. of soil. Many deciduous trees utilize moisture from depths of 8 to 12 ft. Some other crops, such as strawberries, require continuously available moisture in the upper 1 or 2 ft. during periods of ripening.

References

1. DAVIS, R. O. E., and H. H. BENNETT: Grouping of Soils on the Basis of Mechanical Analysis, *U. S. Dept. Agr. Dept. Circ.* 419, 1927.
2. BRIGGS, L. J., and H. L. SHANTZ: The Wilting Coefficient for Different Plants and Its Indirect Determination, *U. S. Dept. Agr. Bur. Plant Indus. Bull.* 230, 1912.
3. MCLAUGHLIN, W. W.: Capillary Movement of Soil Moisture, *U. S. Dept. Agr. Bull.* 835, 1920.
4. ———: Capillary Distribution of Moisture in Soil Columns of Small Cross-section, *U. S. Dept. Agr. Bull.* 1221, 1924.
5. WADSWORTH, H. A., and A. SMITH: Some Observations upon the Effect of the Size of the Container upon the Capillary Rise of Water through Soil Columns, *Soil Science*, vol. 22, p. 199, 1926.

6. Scofield, C. S., and C. C. Wright: The Water Relations of Yakima Valley Soil, *Jour. Agr. Research*, vol. 37, No. 2, 1928.
7. Veihmeyer, F. J.: Some Factors Affecting the Irrigation Requirements of Deciduous Orchards, *California Agr. Exp. Sta., Hilgardia*, vol. 2, No. 6, 1927.
8. Sievers, F. J., and E. G. Schafer: Sugar Beets under Irrigation in Washington, *Washington Agr. Exp. Sta. Bull.* 154, 1919.
9. Loughridge, R. H.: Distribution of Water in the Soil in Furrow Irrigation, *U. S. Dept. Agr. O. E. S. Bull.* 203, 1908.
10. Beckett, S. H., H. F. Blaney, and C. A. Taylor: Irrigation Water Requirement Studies of Citrus and Avocado Trees in San Diego County, Calif., 1926 and 1927, *California Agr. Exp. Sta. Bull.* 489, 1930.
11. Packard, W. E.: Irrigation of Alfalfa in Imperial Valley, *California Agr. Exp. Sta. Bull.* 284, 1917.
12. Beckett, S. H., and M. R. Huberty: Irrigation Investigations with Field Crops at Davis and at Delhi, Calif., 1909–1925, *California Agr. Exp. Sta. Bull.* 450, 1928.
13. Kiesselbach, T. A., J. C. Russel, and A. Anderson: The Significance of Subsoil Moisture in Alfalfa Production, *Jour. Am. Soc. Agron.*, vol. 21, No. 3, 1929.

CHAPTER III

DISPOSAL OF IRRIGATION WATER APPLIED TO THE SOIL

Of the water applied to land, a part may pass across the soil and be lost as surface waste or run-off. Of the remainder which is absorbed by the soil, a part may be evaporated from the soil surface and a part may percolate through the soil below the reach of plant roots. The remainder of the water applied is retained in the soil within reach of the plant roots and is available for transpiration. The proportion of the total water applied which is transpired by the crops is a measure of the efficiency of the irrigation practice. The three items of loss may be reduced by proper practice, and where economic conditions justify the expense such losses may be limited to a small proportion of the total application. However, even under favorable conditions all losses cannot be avoided. Present average practice leaves much room for improvement. Such improvement is occurring with experience in use in the irrigated areas.

SURFACE WASTE

This term is used to describe the part of the water applied to a field which flows across the area being irrigated and escapes on to lower areas or into wasteways. Its amount may vary from nothing to a large percentage of the water applied. Surface waste is more difficult to control on steep lands on which the water flows rapidly or on heavy soils where the slow rate of absorption results in much of the water reaching the lower end of the run. On flat lands of coarse soil, surface waste is seldom an important factor, the problem of irrigation practice being to get water across such lands effectively rather than to prevent surface waste.

Surface waste from one field may not be lost from the farm as it may be picked up and reused on lower fields. Similarly surface waste from the farm may not be lost to the irrigation system as it may be caught and reused on lower farms. The surface waste from upper-canal systems may return to the stream and be

available for diversion by lower canals. Surface waste is a loss for the area on which the water is applied and the supply required for delivery to the land needs to be large enough to include reasonable surface waste.

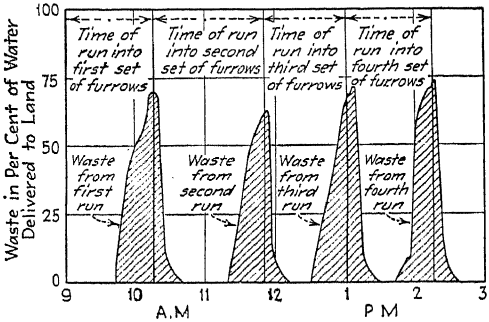


FIG. 14a.—Waste of water delivered to 200-ft. furrows on loam soil 12 in. deep over clay hardpan. Slope, 1 per cent; flow per furrow, 0.04 sec.-ft.; crop, potatoes; average time of set, 1⅓ hr.; average depth of water applied, 0.27 ft.; average waste, 21 per cent.

Where water is expensive or where it is difficult to secure an outlet for waste water, the amount of waste is usually small or is entirely prevented. The landowner is responsible for the water discharged from his farm if it causes damage to adjacent farms or roads. Flooding of highways is a misdemeanor in the western

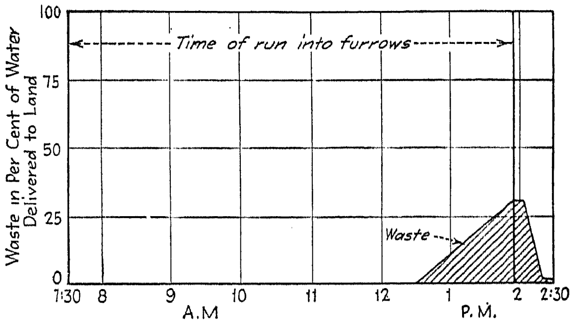


FIG. 14b.—Waste of water delivered to 318-ft. furrows on sandy loam soil 18 in. deep over gravel. Slope, 4 to 5 per cent; flow per foot width of run, 0.025 sec.-ft.; crop, alfalfa, average depth of water applied, 1.68 ft.; average waste, 5 per cent.

states. A few prosecutions for such flooding in any locality usually result in a reduction in the amount of surface waste.

In Fig. 14 are shown the results of measurements of waste from furrow irrigation near Reno, Nev. On the heavier soil (Fig. 14a),

water reached the lower end of the furrow quickly and the waste soon equaled two-thirds of the supply delivered. Longer times of run in the furrow would have shown almost 100 per cent waste as the soil over the nearly impervious hardpan could absorb little additional water. A shorter time of run would have given nearly as large depths of absorption with a smaller average percentage of waste. On the coarser soil (Fig. 14*b*), a very heavy irrigation was absorbed before any water wasted from the lower end of the furrows. The problem in such cases is to get the water over the land without applying water in excess of the moisture capacity of the soil and causing deep percolation losses. While surface waste was small in this case, probably over two-thirds of the water applied penetrated into the soil below the depth from which it would be available to the crop roots.

Measurements of surface waste from many single fields in Idaho using the corrugation method of irrigation gave the following results:[1]

Crop	Soil	Average percentage of surface waste
Alfalfa	Clay loam	19
Grain	Clay loam	25
Alfalfa	Gravelly	2
Grain	Gravelly	2.5

Waste from entire farms would be less than these amounts. It was concluded that, on medium to heavy soils with this method of irrigation, provision should be made in planning deliveries to farms for surface waste amounting to 7.5 to 12.5 per cent of the water delivered. Measurements in Montana with wild-flooding methods indicated that 5 per cent waste on medium soils was a sufficient allowance. On lands prepared in checks by enclosing leveled areas with levees, surface waste should be negligible in amount. Furrow irrigation in orchards or row crops requires careful regulation to prevent from 5 to 10 per cent waste on heavier soils or steeper slopes. With care in handling water, surface waste can be largely or entirely eliminated even under unfavorable soil and topographic condition. Such results are obtained in the citrus practice of Southern California.

ABSORPTION

The rate at which soils absorb water varies widely. On coarse soils with adequate underdrainage, absorption may continue as long as water is applied to the surface at a fairly uniform rate of 2- to 5-ft. depth of water per 24 hr. Efficient irrigation requires covering such lands quickly if the depth applied is not to exceed the moisture holding capacity of the soil. At the other extreme are some heavy soils which crack when dry and swell when wet. On the gumbo soils of the Belle Fourche Project,[2] drying forms a natural mulch about 2 in. thick with cracks extending to 15-in. depth. When irrigated, after the cracks and surface soil have been filled, little further absorption can be obtained and longer times of run of water over the surface result in little further absorption. Similarly slow rates of absorption occur on the clay adobe soils used for rice in the Sacramento Valley, where water is ponded on the land for over 90 days during the period of crop growth with very little absorption by the soil.

When water is turned on to land in flooding methods or started in furrows in furrow practice, as the water first comes into contact with the soil an initial absorption takes place quickly as the dry surface soil becomes saturated. Further absorption is at a slower rate which with the medium and coarser soils will continue as long as the water is applied, unless the soil becomes fully saturated to the depth of some impervious subsoil. By the time the water has reached the lower end of the run, the upper end will have received its initial absorption plus the continued absorption during the time of the run. If the water is then shut off, the upper end of sloping runs becomes unwatered first and some continued absorption will occur on the lower end as the flow drains down the slope. If water is allowed to continue to flow into the run after it reaches the lower end, absorption will continue over the whole area during the time of such run.

These conditions are illustrated in Fig. 15 for sloping land. The uniformity of distribution over the area depends on the amount of absorption while the water is progressing across the run. If a small stream which progresses slowly is used, the absorption at the upper end during the advance of the flow may be a major part of the total application. Absorption while water is draining from the run is usually much less than that during the advance of the flow, as the time of draining is shorter.

To secure relatively uniform distribution on coarse soils, water must be gotten across the runs quickly. This can be accomplished by using large heads of water or short runs. Very coarse soils will absorb 3 to 6 in. initially and continue to absorb at the rate of 2 to 4 in. per hour. If it takes an hour for water to reach the lower end of the run, the absorption at the upper end may be double that at the lower end on such soils. As the initial absorption is nearly equal to the moisture capacity of these soils to the usual depth of use of moisture by crops, it is not necessary to have water run for more than a short period in order to secure an adequate depth of application. Irrigations in which an average depth of water of 6 in. is applied may consist of an absorption of

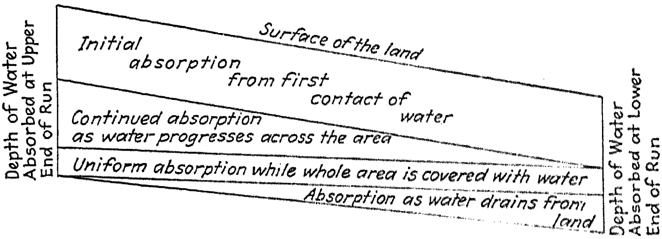


FIG. 15.—Character and distribution of absorption from an irrigation over length of run of water on sloping land.

as much as 9 in. at the upper end and 3 in. at the lower. A distribution of 7 in. at the upper end and 5 in. depth at the lower would represent good results.

On heavy soils it is difficult to secure adequate absorption. On some heavy soils, not over 2- or 3-in. depth of water will be absorbed at an irrigation. In some cases additional absorption may be secured by repeating the irrigation after the soil has had a few hours for the first application to enter the soil more deeply and for the entrapped air in the lower soil to escape. Heavy soils require frequent irrigation owing to the small amount of absorption obtainable. While the pore space and actual moisture holding capacity of heavy soils are large, such capacity cannot be fully utilized owing to the difficulty of movement of moisture through the very many but very small pore spaces.

Effect of Length of Run.—The effect of length of run of water over the land in field flooding is illustrated by observations made in Idaho on a gravelly soil.[3] On a field in which the water was run nearly ½ mile in a strip about 100 ft. wide, the time required

for the water to cover each successive one-eighth of the total length of run was observed. A constant head of 7 sec.-ft. was delivered. The results are shown in Table III.

TABLE III.—EFFECT OF LENGTH OF RUN OF WATER IN FIELD FLOODING ON AMOUNT OF WATER ABSORBED[3]

Division number	Total length of run, feet	Time required to cover each division		Total acre-feet delivered	Average depth delivered, feet	Depth delivered on added area covered, feet
		Hours	Minutes			
1	327	0	45	0.43	0.62	0.62
1–2	653	1	40	0.96	0.68	0.75
1–3	980	2	50	1.63	0.76	0.93
1–4	1,307	4	15	2.44	0.85	1.08
1–5	1,634	6	15	3.59	0.99	1.53
1–6	1,960	8	15	4.74	1.08	1.53
1–7	2,287	10	30	6.04	1.17	1.67
1–8	2,566	13	15	7.62	1.33	2.87

Table III shows that water had to be run into this area for over four times as long to cover the last one-eighth of the length as for the first one-eighth. As water traveled down the area, part of the supply was absorbed by the area already covered leaving a smaller flow to push on over the remaining length. Toward the lower end the flow remaining was so small that progress was very slow. If this field had been divided with ditches and water turned directly into each division, it could have been covered with less than one-half of the water used on the long run as each portion would use an amount similar to the first division. A saving of 36 per cent in the water used could have been made by using two runs of one-half the length used.

Effect of Size of Irrigating Head.—The effect of the size of head on the amount of water needed to cover the land is shown by the three curves in Fig. 16. Curve 1 represents a compact volcanic-ash and adobe soil with a length of run of 615 ft. Reducing the size of head used from 0.8 to 0.4 sec.-ft. per acre nearly doubled the depth of water required to cover this fairly heavy soil. Curve 2 represents a wind-blown ash and sandy soil with coarse subsoil with a length of run of 1,350 ft. A small reduction in size of stream doubled the amount of water required. Curve 3

shows the results for a soil consisting of a thin layer of ash and sand over coarse gravel with 515-ft. runs. Even for this length of run a 40 per cent reduction in size of head resulted in a 100 per cent increase in the water required.

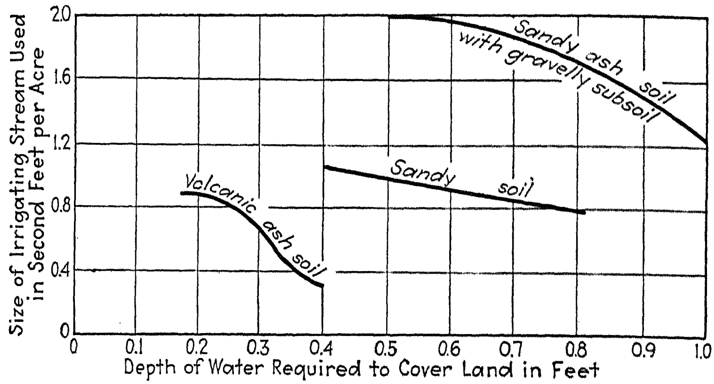


FIG. 16.—Relation of size of head used and depth of irrigation required for three fields from experiments in Idaho. (*Adapted from Steward.*[4])

Figure 17 shows the effect of size of head on depth of irrigation with border checks based on observations on the Carlsbad Project in New Mexico. As these checks are of uniform width for their full length, the size of head is expressed in terms of the rate of

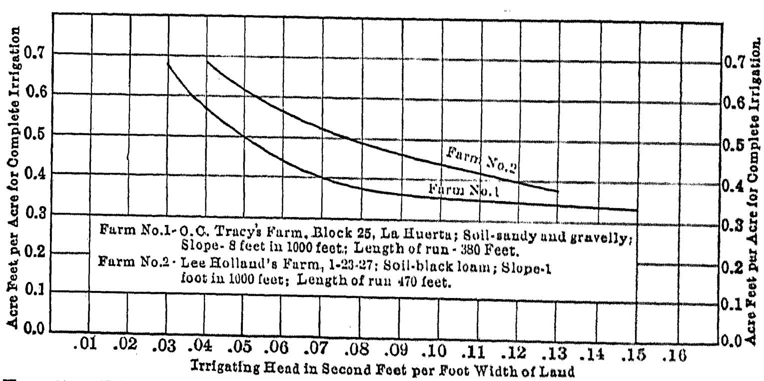


FIG. 17.—Effect of head of water on depth of irrigation in flooding by border method. Carlsbad Project, New Mexico.

flow per foot width of check. A relatively rapid decrease in the depth of water required with an increase in the size of head is shown for the smaller sizes of head. For sizes of head of over 0.1 sec.-ft. per foot width of check less difference occurred.

Similar results are shown by observations on 1-acre border checks having a slope of $3\frac{1}{2}$ in. per 100 ft. at Davis, Calif. The soil is a loam.[5]

Rate of Application, Cubic Feet per Second per Acre	Depth of Water Required per Irrigation, Feet
4.6	2.75
10.1	1.86
13.5	1.16
15.3	0.84
17.8	0.69

Measurements in the Sacramento Valley[5] indicated that the average size of head used per acre was 23 sec.-ft. for gravelly loams, 11 sec.-ft. for sandy loams, 9 sec.-ft. for silt loams, 7 sec.-ft. for clay loams, and 3 sec.-ft. for clays. Actual checks used are generally less than 1 acre in area, so that the actual heads used were less than the amounts stated, such as using 6 sec.-ft. on quarter-acre checks on gravelly loams. For good practice, sizes of checks and heads should be adjusted so that alfalfa on coarse soils can be covered evenly without using in excess of an average depth of irrigation of 6 in.

DEEP PERCOLATION

Deep percolation is the moisture which penetrates below the depths from which it may be used by plants. It represents the part of the water absorbed which exceeds the field capacity of the soil within the depth of root development. The amount of deep percolation depends upon the amount of water absorbed, the dryness of the soil at the time of irrigation, and the moisture holding capacity of the soil. Such deep percolation is difficult to prevent on coarse soils where excess water may be absorbed before the water has reached the lower ends of the irrigated area. It is seldom a serious problem on heavy soils.

Deep percolation on an individual field represents a loss in the irrigation practice for that field. Such percolation, together with the seepage from the canals, produces a rise in the ground water which frequently results in waterlogging unless removed by natural or artificial drainage. While drainage water or natural return flow to streams is available for reuse and is a source of water supply on many streams, much injury to irrigated lands has been caused by overuse with resulting leaching of soil fertility, waterlogging, and alkali.

Observations of deep percolation are difficult to make directly, as the percolating water cannot be segregated for measurement under field conditions. Some experiments have been made by placing soil in tanks or lysimeters, from which the moisture passing through the soil from different amounts of irrigation is collected by some method of drainage. Such drainage does not occur from the tanks until the soil in the bottom of the tank has become nearly saturated. Under field conditions, downward moisture movement into deeper soil occurs as soon as the soil moisture approaches the field capacity. Lysimeters tend to indicate less percolation than would occur under field conditions.

Field observations of percolation are more usually made by accounting for the other parts of the water applied and charging the remainder to percolation. The observations consist in the measurement of the total water applied less any surface waste and in soil-moisture samples taken before and after the irrigation. The difference between the water absorbed by the soil and the sum of the increase in soil moisture and the evaporation and transpiration between the times of soil-moisture sampling represents the deep percolation. The evaporation and transpiration for the time between soil-moisture samplings are usually relatively small in relation to the percolation on coarser soils and may be estimated and deducted or included with the percolation. The period between moisture samplings is usually 1 to 3 days in order to give time for the main moisture distribution to take place.

The water holding capacities of soils have been discussed in Chap. II. The following examples illustrate the amount of percolation that may occur under different conditions.

Observations of Percolation from Tanks.—A striking example of large percolation loss on coarse gravelly soil is shown in Table IV, based on observations in tanks made in Idaho.[3] It was found that large amounts of water were being applied under field conditions and it was desired to measure the proportion of the water applied which percolated below depths of 6 ft. In 1911, soil was placed in tanks 6 ft. deep and given the same depths of irrigation at the same times as the adjacent field. The percolation was found to be about five-sixths of the water applied. In 1912, the experience of 1911 was used and the water applied to the tanks was limited to the amount retained from an irrigation in 1911. In 1912, no percolation occurred except from the first irrigation which was intentionally made somewhat heavier in

order to be sure to moisten the full depth of the tank. Alfalfa had been seeded in the tanks in 1911, and in 1912 it made just as thrifty growth and went as long between irrigations without drought injury with irrigations of about 2-in. depth as the alfalfa in the adjacent field which was given irrigations of about 1 ft. in depth at the same frequency. These results indicate that on such coarse soils the moisture holding capacity for the upper 6 ft. of soil may be as small as ⅓-in. depth of water per foot depth of soil. The effort of practice should be to get the water over such lands with as little application in excess of 2- to 3-in. total depth as practicable. Such results require large heads and short runs. While this soil is unusually coarse and has a very small moisture holding capacity, it is a forceful illustration of the principles involved and the large percolation losses that may occur under unfavorable conditions.

TABLE IV.—PERCOLATION FROM GRAVELLY SOIL IN TANKS 6 FT. DEEP, GROWING ALFALFA[3]

Season of 1911			Season of 1912		
Date of irrigation	Depth of irrigation, feet	Depth of percolation, feet	Date of irrigation	Depth of irrigation, feet	Depth of percolation, feet
May 31	1.10	0.69	May 28	0.30	0.12
June 14	0.71	0.66	June 21	0.15	Trace
July 8	0.83	0.80	July 2	0.15	Trace
Aug. 1	0.64	0.51	July 6	0.15	0
Aug. 9	1.09	0.96	July 13	0.15	0
Aug. 31	1.14	0.94	July 21	0.15	0
Sept. 24	1.08	0.95	July 28	0.15	0
			Aug. 8	0.15	0
			Aug. 13	0.15	0
			Sept. 2	0.15	0
Total	6.59	5.51	Total	1.65	0.12
Precipitation, June to Sept	0.31	....	Precipitation, April to Aug	0.71	

Results of experiments at Umatilla, Ore., in lysimeters 6 ft. deep and 3.3 ft. square filled with soil of different textures are shown in Table V.[6] The water applied to these tanks was all

absorbed and used by evaporation, transpiration, or percolation. For tanks 1 to 4 of medium sand to which about 5-ft. depth of water per season was applied in individual irrigations of about 3-in. depth, little percolation occurred on the tanks growing alfalfa; for the bare tank, over two-thirds of the water percolated, the remainder being evaporated. Percolation was continuous between irrigations from the bare tank. For the tanks filled with the other soils, percolation was in general proportional to the coarseness of the soil. On the heavier soils, downward movement occurred more slowly and the moisture was evaporated from the soil surface and intercepted and used by the alfalfa roots, before it reached the drain from the tank, for tanks on which the total amount of use per season was about 5 acre-ft. per acre. When the use was increased to about 10 ft. in depth per season, some percolation occurred. For all of these tanks the amounts applied at each irrigation were representative of smaller depths of irrigation than are generally used in field practice on similar soils. Drainage from the tanks would be less than the downward percolation in field soils owing both to the lighter irrigations used and to the necessity of having saturated soil in the bottom of the tank before drainage occurs.

TABLE V.—ANNUAL WATER APPLICATIONS AND PERCOLATION IN LYSIMETER EXPERIMENTS WITH VARIOUS TYPES OF SOIL AND CROPS AT THE UMATILLA FIELD STATION, 1915 TO 1925[6]

Tank number	Soil	Crop	Years of observation	Annual depth applied, inches	Annual depth of percolation, inches	Percentage of percolation
1	Medium sand	None	11	58.4	41.1	70.0
2	Medium sand	Soy beans and vetch	11	58.2	25.2	43.5
3	Medium sand	Alfalfa	11	58.4	10.8	19.1
4	Medium sand	Alfalfa, manured	11	58.4	8.9	16.0
5	Fine sand	Alfalfa	9	60.3	5.0	8.7
6	Coarse sand	Alfalfa	9	60.3	15.2	25.5
7	Silt	Alfalfa	5	56.6	0	0
7	Silt	Alfalfa	3	121.5	13.3	12.0
8	Silt loam	Alfalfa	5	57.2	0	0
3	Silt loam	Alfalfa	3	121.5	14.5	11.9

Observations of Percolation under Field Conditions.—Experiments under field conditions based on soil-moisture determinations on the sandy soils on the Minidoka Project in Idaho, where water was applied in level rectangular checks in alfalfa, gave the following results:

Depth of irrigation, inches	Depth of water retained in upper 5 ft. of soil, inches	Depth retained, percentage of depth applied
Less than 4.0	3.4	100
4.0 to 5.0	3.9	88
5.0 to 6.0	3.6	66
6.0 to 7.0	4.2	63
7.0 to 9.0	4.0	52
Over 9.0	4.1	30

This sandy soil was able to retain only about 4-in. depth of water above the coarse sand which occurs at the 5-ft. depth. The amount retained was not increased by the heavier irrigations. The alfalfa went as long between irrigations without injury with the lighter irrigations as with the heavier applications. For efficiency in the use of water, such soils should be prepared so that they can be irrigated without using over 4-in. depth of water per irrigation.

TABLE VI.—DISTRIBUTION OF TOTAL SOIL MOISTURE BEFORE AND AFTER IRRIGATION, LOGAN, UTAH

Depth of water applied, inches	Number of trials	Before or after irrigation	Percentage of total moisture by weight in each foot depth of soil								Mean percentage of total moisture for 8 ft. of soil
			1	2	3	4	5	6	7	8	
2.5	23	Before	9.57	10.55	11.78	12.97	11.92	11.41	11.75	11.49	11.43
		After	19.24	13.70	13.17	13.84	12.66	12.72	12.31	12.70	13.67
		Increase	9.67	3.15	1.39	0.87	0.74	1.31	0.56	1.21	2.24
5.0	115	Before	12.97	14.08	15.68	16.09	15.21	15.18	14.77	13.92	14.74
		After	23.92	20.71	19.27	17.95	16.25	15.79	15.60	14.81	18.04
		Increase	10.95	6.63	3.59	1.86	1.04	0.61	0.83	0.89	3.30
7.5	44	Before	10.62	12.44	14.44	15.11	14.20	13.40	13.13	13.27	13.33
		After	23.83	21.83	20.05	17.40	15.87	14.66	14.21	14.15	17.75
		Increase	13.21	9.39	5.61	2.29	1.67	1.26	1.08	0.88	4.42

The distribution of irrigation in a heavy loam soil in Utah from irrigations of different depths is shown in Table VI,[7] based on soil-moisture samples taken just before and shortly after irrigation. This soil has a dry weight of 76 lb. per cubic foot. The additional depth of water found after irrigation equaled 2.6 in. for the 2.5-in. irrigation, 3.85 in. for the 5-in. irrigation, and 5.15 in. for the 7.5-in. irrigation. The excess for the 2.5-in. irrigation represents the inaccuracy of soil-moisture sampling. The unaccounted-for water for the 5- and 7.5-in. irrigations represents the percolation below 8 ft. and the evaporation and transpiration between the times of sampling. Some increase in soil moisture is shown for each foot of soil depth for all irrigations, the increase in the upper 3 ft. being larger than that at greater depths.

SOIL-MOISTURE EVAPORATION

The amount of evaporation of moisture from soil depends on the availability of moisture at the surface of the soil and on the atmospheric conditions. In most arid regions atmospheric conditions during the irrigation season are generally favorable to relatively rapid evaporation. Soil-moisture conditions are also favorable during and just following surface irrigations. Soils wet at the ground surface will have a rate of evaporation somewhat larger than that from a water surface owing to the higher temperature of the soil. As soon as the surface of the soil becomes dry, the amount of evaporation is determined by the rate at which capillary movement may bring moisture to the surface to replace the moisture that has evaporated. The drying of a few inches of the surface soil materially reduces the rate of such capillary movement with a corresponding reduction in the rate of evaporation.

There has been a large amount of experimental investigation of soil-moisture evaporation under both dry-farming and irrigation practice. As the results of the more complete studies have become available, earlier conclusions have been adjusted and field practices for the prevention of evaporation have been modified. Much of the experimental work has been based on an effort to determine the extent to which moisture in the soil could be protected from evaporation by the use of soil mulches. The view was formerly generally held that the formation of a surface mulch destroyed the capillary continuity of the soil and reduced

the rate of evaporation. Frequent cultivation to maintain the soil mulch was common in summer fallow practice in dry farming, and in orchards and other irrigated crops which permitted such cultivation. Further studies have shown that, where the soil moisture is much below the field capacity, capillary movement occurs relatively slowly and little soil-moisture evaporation takes place after the surface soil has become dry either with or without a soil mulch. Sufficient cultivation to prevent loss of moisture by transpiration by weeds should be practiced. Such transpiration from even a limited amount of weed growth may be several times the amount of evaporation from the soil.

Where ground water occurs near the ground surface and furnishes a continuing source of moisture supply for capillary movement, mulching will result in a reduction in the soil-moisture evaporation. Ground water occurs at such depths under much irrigated land. More frequent cultivations for both weed and evaporation control are needed under such conditions.

Experimental Methods.—Observations of soil-moisture evaporation have usually been made on uncropped soils. With growing crops, soil-moisture evaporation is reduced owing to the shading by the crop and is also further reduced by the interception and use by the plant roots of moisture which might otherwise reach the soil surface and be evaporated. Owing to such conditions the numerical results of experiments on soil-moisture evaporation represent larger amounts of loss than would occur under usual conditions on irrigated lands.

Observations of soil-moisture evaporation have been made by the use of tanks and by soil-moisture sampling in the field. Tank methods permit a more close control but may introduce conditions differing from those applying in the field. Excess moisture may accumulate in the lower portions of the tanks within capillary reach of the surface so that the amount of evaporation exceeds that which occurs under field conditions on drained soils. Other factors affecting the results are the size of the tank and methods of securing temperatures in the soil in the tank similar to those in the field. Typical equipment for tank experiments is shown in Fig. 18.

As the amount of soil-moisture evaporation is usually a small part of the total soil moisture, field observations by means of soil-moisture samples require care and repetition to secure dependable results. A large amount of such work has been done

mainly where ground water was too deep to affect the evaporation and usually on soils that were relatively dry.

The results of experiments on soil-moisture evaporation which follow have been divided into three groups based on the general moisture conditions of the soil. These groups are (1) those in which the soil is saturated at known depths below the surface, (2) those in which the soil moisture was in excess of field capacity but not in contact with a continuing water table, and (3) those in which moisture was not available in excess of the field capacity.

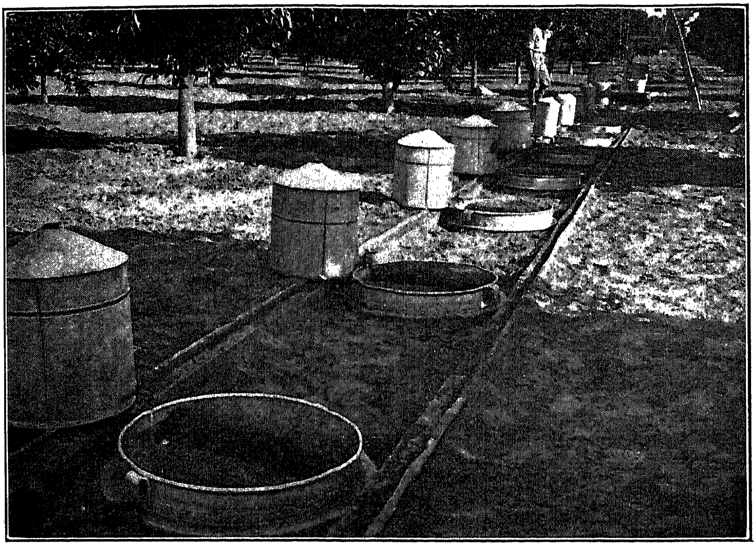


FIG. 18.—Tanks used for experiments on evaporation. (*Fortier*.[17])

Evaporation from Soils with Shallow Water Table.—Results from experiments at Denver, Colo., where water was maintained at different depths below the soil surface in 2-ft. diameter tanks filled with a sandy loam soil, are shown in Table VII.[8] With water 4 in. below the surface, the soil-moisture evaporation was nearly as large as that from a free water surface. As the depth of the water table increased, the moisture in the top soil decreased with a corresponding reduction in the rate of soil-moisture evaporation. Little evaporation would occur from this soil with the water table more than 4 ft. below the surface.

Evaporation from 8-in. diameter columns of loam soils of different length with an initial moisture content equal to the field

TABLE VII.—EFFECT OF DEPTH OF WATER TABLE ON SURFACE SOIL MOISTURE AND EVAPORATION FROM SANDY LOAM SOIL[8]

Depth to water table from soil surface, inches	Moisture in top 4 in. of soil, per cent by weight	Evaporation from soil during 65-day period, inches	Evaporation from soil, per cent of evaporation from water surface
4	18.9	11.34	88
16	16.2	10.26	80
28	13.2	8.02	62
38	9.6	4.24	33
43	7.9	0.98	8
50.5	6.3	0.93	7

capacity and with their lower ends in contact with water is illustrated by laboratory observations at Berkeley and Davis, Calif.[9] The tubes were filled with carefully packed soil, irrigated until drainage occurred, allowed to complete the drainage, and the lower ends set in water. The water drawn into the tubes by capillary action and evaporated was measured over a period of 10 months. The average results for two tubes of each length were as follows:

Length of Tube, Feet	Average Rate of Evaporation from Soil Surface, Inches Depth per Month
4	1.35
6	0.74
8	0.38
10	0.065

After the completion of these observations, the soil-moisture distribution in the tubes was determined, with the results shown in Fig. 19. A gradual reduction in moisture content from the water surface at the bottom of the soil columns to the soil surface was shown. When free to drain, this soil retained about 20 per cent moisture by weight. The lower portions of the soil columns retained more moisture than the field capacity when free to drain; soil-moisture evaporation reduced the upper portions below the field capacity. These results indicate that capillary action is not effective in raising moisture in this soil for heights above the water table of more than about 10 ft.

The effect of mulching on soil-moisture evaporation where the water table is within capillary reach of the soil surface is illus-

trated in Fig. 20, based on laboratory observations in California on columns of loam soil, 4 ft. high.[10] The mulched tanks were

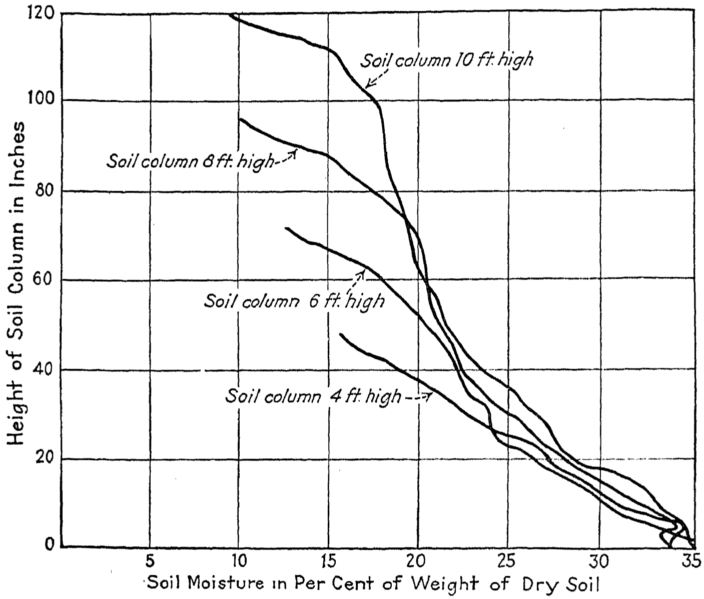


FIG. 19.—Distribution of moisture above a water surface in columns of loam soil 4, 6, 8, and 10 ft. high after 10 months. (*Shaw and Smith.*[9])

cultivated at the beginning of the experiment, about 6 months later, and at about monthly periods during the remainder of the

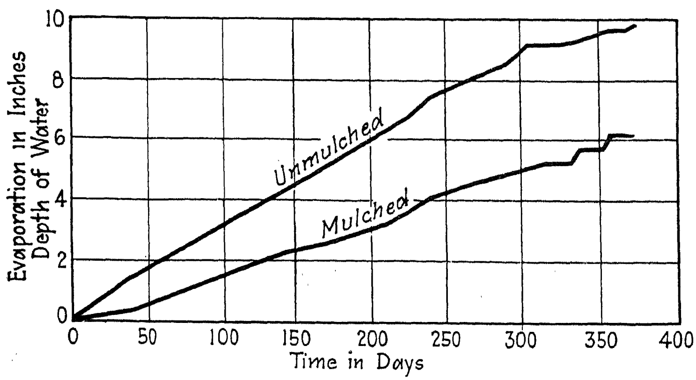
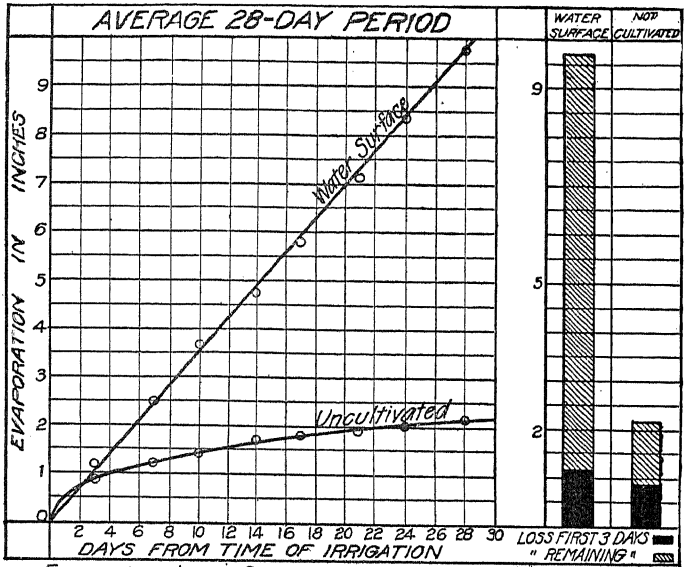


FIG. 20.—Evaporation under laboratory conditions from 4-ft. columns of loam soil with water at base of column. (*Adapted from Shaw.*[10])

period. Mulching under these conditions reduced the soil-moisture evaporation by 38 per cent.

Evaporation from Soils with Moisture in Excess of Field Capacity.—In several experiments on soil-moisture evaporation, tanks have been used in which the depth of irrigation applied was sufficient to raise the soil moisture above the field capacity without creating or maintaining a permanent water table at any fixed depth. Such experiments are of interest as indicating the relative losses that may occur from soils having impervious subsoils at depths of 4 to 5 ft. where excess moisture may collect above the subsoil following an irrigation.



Evaporation losses from uncultivated soil, & free water surface.

FIG. 21.—Evaporation loss from uncultivated bare soils in tanks following an irrigation. (*Adapted from Fortier and Beckett.*[11])

Figure 21 illustrates the average results obtained with such tank observations at six different stations during summer periods.[11] The tanks were 4 ft. deep. A 6-in. irrigation was applied under conditions which would result in moisture in excess of the field capacity in the lower portion of the tanks. The tanks were uncropped and uncultivated. The evaporation from a water surface in similar tanks is also shown. The evaporation from the soil during the first few days following the irrigation was as large as that from the water surface, nearly one-half of the total loss for the 28-day period occurring in the first 4 days. Some evaporation at a relatively slow rate was still occurring at

the end of the period. Of the 6-in. depth of irrigation applied, the remaining 4 in. was still held by the soil in the tanks and had not been returned to the surface by capillary action.

A comparison of the difference in evaporation with and without cultivation of the soil is shown in Table VIII and Fig. 22. These results were secured in observations in tanks under similar conditions to those described for Fig. 21. As the moisture of the soils in the tanks was above field capacity, the amounts of evaporation and the indicated saving due to cultivation exceed what would be obtained under field conditions with dryer soils. About one-half of the total loss from the cultivated tanks occurred in the

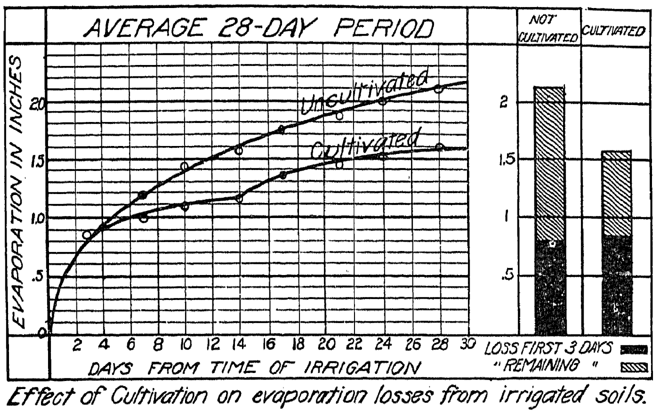


Fig. 22.—Evaporation loss from cultivated and uncultivated bare soils in tanks following a 6-in. irrigation. (*Adapted from Fortier and Beckett.*[11])

first 3 days after irrigation before the soils were sufficiently dry to permit cultivation. For the conditions of these experiments, a saving in evaporation due to cultivation of about 0.5-in. depth of water was obtained.

The differences in evaporation between flooding the entire soil surface and partial flooding with furrows is illustrated by the results shown in Fig. 23. These observations were made in tanks similar to those used in the results shown in Figs. 21 and 22. The smaller loss shown for the deeper furrows was due to the smaller proportion of the surface soil which was wet. These tanks were given a 6-in. depth of irrigation, followed by cultivation as soon as practicable. The continued rate of evaporation during the 28-day period indicates a higher soil-moisture content than would occur under field conditions.

TABLE VIII.—EFFECT OF CULTIVATION ON SOIL-MOISTURE EVAPORATION FROM TANKS FOR 28-DAY PERIOD[11]

Locality of experiment	Total rain-fall, inches	Evapora-tion from free water surface, inches	Evapora-tion from culti-vated soil, inches	Evapora-tion from unculti-vated soil, inches	Difference in evapora-tion from unculti-vated and cultivated soil, inches
Sunnyside, Wash.	0	7.25	1.47	2.47	1.00
Davis, Calif.	0	9.41	1.36	1.91	0.55
Reno, Nev.	0.39	8.49	1.09	1.51	0.42
Caldwell, Idaho	0.14	9.81	1.91	2.42	0.51
Agricultural College, N. M.	0.57	11.13	1.37	1.59	0.22
Bozeman, Mont.	0.99	4.38	2.30	2.92	0.62
Mean	0.35	8.41	1.58	2.14	0.56

Evaporation from Soils at or below Field Capacity.—Evaporation from tanks where the soil moisture had been brought to the field capacity of the soil both uncultivated and with different depths of mulch is shown in Fig. 24, based on observa-

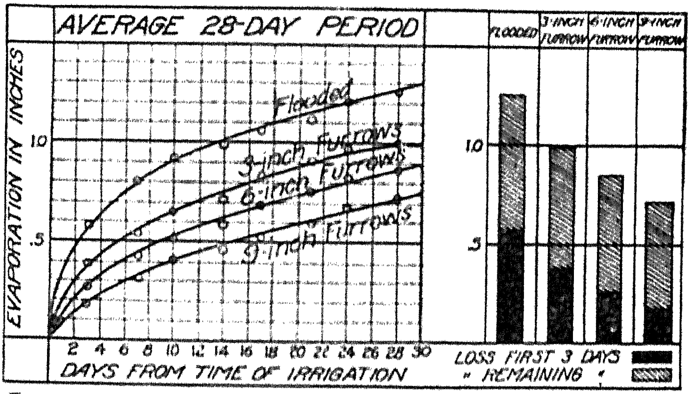


FIG. 23.—Evaporation loss from uncultivated soil in tanks irrigated by flooding and by furrows. (*Adapted from Fortier and Beckett.*[11])

tions in tanks at Mountain View, Calif., in 1921.[12] For all treatments the loss during the first week following the irrigation was approximately one-half of the total loss for the 80-day period. The uncultivated tank was undisturbed except to pull any weeds

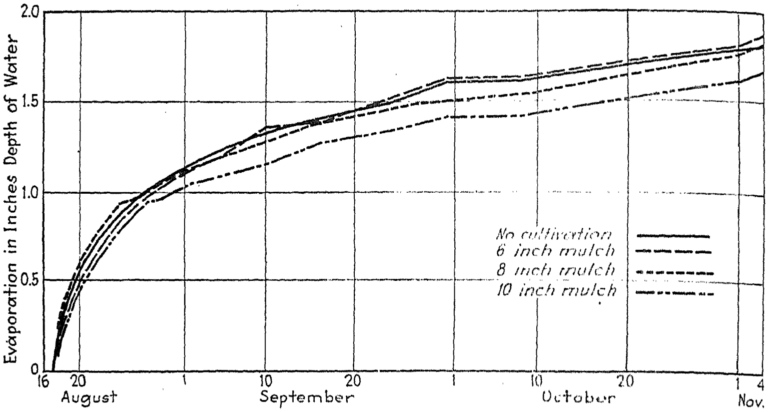


FIG. 24.—Evaporation from clay loam soil in tanks 4 ft. deep without plant growth following an irrigation to field capacity. (*Veihmeyer.*[12])

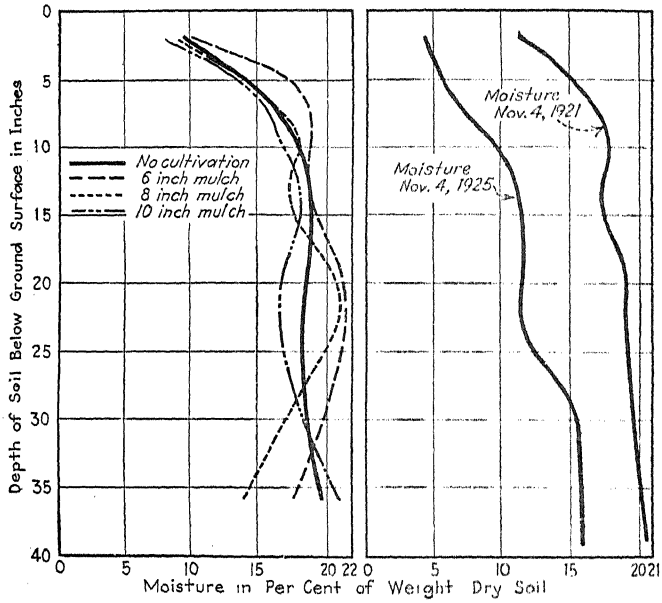


FIG. 25.—Moisture distribution in clay loam soil 80 days after irrigation. (*Adapted from Veihmeyer.*[12])

FIG. 26.—Drying out of uncropped and uncultivated clay loam soil in 4 years. (*Adapted from Veihmeyer.*[12])

which started to grow. For the entire period the average loss from the three depths of cultivation was 1.8 in., which was equal numerically to the average loss from the uncultivated tanks. No water was added to these soils after the beginning of the experiment. These results indicate the amount of loss that occurs from bare soils raised to field capacity where the moisture evaporated is not replenished.

TABLE IX.—SUMMARY OF MOISTURE CONTENT IN 4-IN. DEPTHS OF SOIL IN CULTIVATED AND UNCULTIVATED PLOTS[12]
From experiments in California

Location of plots	Texture of soil	Depth of soil samples, inches				
		0 to 4	4 to 8	8 to 12	12 to 16	16 to 20
		Moisture, per cent by weight				
Davis:						
Cultivated	Loam	6.6	15.7	20.1	19.1	18.6
Uncultivated	....	8.6	15.5	19.0	19.0	19.4
Mountain View:						
Cultivated	Clay loam with gravel	4.0	9.5	10.2	10.3	10.7
Uncultivated	....	3.9	9.1	10.4	11.0	10.9
Delhi:						
Cultivated	Fine sand	1.3	3.9	4.1	4.1	4.2
Uncultivated	....	1.5	3.1	3.3	3.7	4.1
Whittier:						
Cultivated	Clay	4.1	11.5	15.1	16.2	15.9
Uncultivated	....	4.1	11.0	16.2	17.3	16.5

The distribution of moisture in the tanks at the conclusion of the observations shown in Fig. 24 is shown in Fig. 25. This shows little drying out of the soil below 18-in. depth either with or without mulching. Capillary movement of moisture from the lower depths into the dry surface soil was very slow. As the soil had an average moisture content of about 20 per cent by weight after irrigation 80 days before the soil-moisture samples on which Fig. 25 is based were taken, all the moisture evaporated appears to have been taken from the upper soil.

In Fig. 26 is shown the extent of drying out in one of the unmulched tanks included in the averages shown in Fig. 25 during an additional period of 4 years.[12] During this time the tank was protected from rains but was otherwise exposed to the full drying effects of field conditions. This tank lost 0.77-in. depth of water in the first week after irrigation, 0.83 in. in the next 2½ months, and 2.04 in. in the next 4 years. These results illustrate the slow rate of capillary movement and evaporation loss from soils after the surface has become thoroughly dry where no replenishment of the moisture lost occurs.

Differences in soil moisture under field conditions as determined by soil sampling 2 months after an irrigation obtained from observations on several soils in California are shown in Table IX.[12] These experiments were made during the summer when no rains occurred during the period of the observations. Usual cultivation following irrigation was given to the cultivated plots; the uncultivated areas were undisturbed except to remove all weed growth. These results show no consistent difference in soil moisture under the two practices. On bare soils having no weed or other plant growth where soil moisture is not replenished and the surface soil becomes dry, little further loss by evaporation occurs either with or without cultivation.

PLANT TRANSPIRATION

Many experiments have been made to determine the amount of water transpired by plants. The results are usually expressed in terms of the pounds of water transpired per pound of plant growth produced. The water transpired divided by the crop produced is called the "transpiration ratio." The mature crop, dried or cured, is generally used as the measure of growth. For forage crops the entire growth above ground is used; for cereals separate ratios may be determined for the grain alone and for the combined weight of grain and straw.

The water requirements of irrigated lands cannot be determined by multiplying the yield by an estimated transpiration ratio. Irrigation consists of supplying water to soils at such times as it is needed by crops. The water requirement depends on the amount of water used at each irrigation and the number of irrigations required. Not all of the water applied can be made available for plant transpiration.

The main purpose of the moisture absorbed by plant roots is to convey to the plant the elements of plant food necessary for its growth. In fertile soils more plant food is available and a greater yield may be produced with the same moisture supply. The type of soil probably affects the transpiration ratio only as it affects the available plant food. It may be more difficult to maintain soil fertility in coarse or sandy soils subject to leaching than in soils of heavier texture. Sandy soils under irrigation are generally given greater depths of irrigation than heavy soils. Such larger use on sandy soils is due mainly to the greater losses that occur in placing and retaining within reach of the plant roots the moisture which is actually used by the plants.

Experiments indicate that the rate of transpiration is not reduced with a reduction in available soil moisture until the wilting percentage is approached. Under dry-farming conditions, wheat has been found to be able to exhaust nearly all the available water without a serious reduction in its rate of use. In observations with fruit trees in tanks in California, it was found that the transpiration appeared to vary with the atmospheric evaporating power and the leaf area rather than with the amount of available moisture present in the soil.[12] The trees appeared able to obtain water from the soil as readily when the soil moisture had been reduced almost to the wilting point as when the soil was filled with moisture to the field capacity. In Nebraska with corn,[13] it was found the total transpiration could be reduced by reduction in the available soil moisture but that the reduction in yield was relatively greater than the reduction in transpiration.

Observations on the daily rate of transpiration of alfalfa in tanks show 3, 11, 21, 29, and 36 per cent of the total use per cutting used in each one-fifth of the period of growth.[14] The small use after cutting is due to the small amount of leaf area. With corn, in experiments in Nebraska,[13] the water transpired per week was found to increase until the maximum leaf area is developed. In the next 4 to 5 weeks the rate of use continued large and represented one-half of the total use for the season. The transpiration then decreased rapidly to the maturity of the crop. During the 10-day period of maximum transpiration annual crops used one-fourth of their total requirement for the season and alfalfa one-half of its needs for a single cutting. During the period of maximum use, the daily transpiration was

twelve to sixteen times the dry weight of the crop for small grains, six to nine times for millet and corn, and thirty-six to fifty-six times for alfalfa.

The transpiration ratio is subject to the effect of all the various factors that affect crop yields. The crop yields per acre usually vary more widely than the water used per acre. A small yield on infertile soil may transpire nearly as much water as a large yield on fertile soil. That crop yields are not directly proportional to the available moisture supply is evident from the wide variation in yield of different fields of the same crop in humid localities where all land receives similar amounts of rainfall. Results of experiments to determine the transpiration ratio show a similar wide variation.

Experiments on transpiration have been made mainly in tanks in order to control more closely the measurement of the water used. While tanks permit a close measurement of the results, care is required to maintain conditions of growth similar to those of the same crops under field conditions. The tanks should be as large as can be conveniently weighed and the plants should have a density of stand similar to field growth. Exposure to air circulation, shade, and temperature conditions should be representative of those of large areas in the field. It is difficult to segregate soil-moisture evaporation from transpiration as the loss of weight from tanks includes both of these items. In some experiments, efforts have been made to determine the soil evaporation separately and deduct it from the combined evaporation and transpiration. In other experiments an effort has been made to reduce or eliminate soil-moisture evaporation by supplying moisture sufficiently far below the surface of the soil in the tanks to prevent capillary rise to the surface or to seal the top of the tanks after the plants were of sufficient height so as to prevent circulation of air at the soil surface.

It has been found that the transpiration ratio is affected by the size of the tank, becoming smaller as the size of tank increases. In experiments with corn by the Nebraska Experiment Station,[13] the transpiration ratio was found to vary from 1,180 when pots containing 85 lb. of soil were used to 430 for pots containing 950 lb. of soil.

Results at Akron, Colo.,[15] where plants were grown in pots with the soil surface sealed to prevent evaporation gave general transpiration ratios for cereals from 350 to 500, sorghum 275,

potatoes and sugar beets 400 to 500, and alfalfa 850 to 1,000. Observations in tanks in some humid areas have given results less than one-half of some of these values. A crop yield of 1 ton per acre with a transpiration ratio of 600 represents a transpiration of 5.31-in. depth of water on an acre per ton of yield. In some California practice a cutting of alfalfa with an average yield of about 1 ton per acre is frequently secured with one irrigation of about 6-in. depth. This would represent a transpiration ratio of about 700 if it is assumed that all of the water applied is transpired. Forage plants are relatively large water users, both the transpiration ratio and the total seasonal use being larger than for other types of crop. Crops generally considered as more resistant to drought, such as sorghum, do not show transpiration ratios much below those of some more sensitive crops. Drought resistance is due more largely to the ability to become dormant without permanent injury during periods of moisture shortage than to the ability to make a more effective use of the available water supply.

That crops may make a more efficient use of moisture under field conditions than in tanks is indicated by a comparison of results at Davis, Calif., for alfalfa in tanks[16] and in the field.[r] Water was applied to the tanks below the soil surface to avoid surface wetting and evaporation. For the first year's growth in the tank, the transpiration ratio was 1,106, and for the second year 708. On adjacent fields of the same soil and climatic conditions, unirrigated alfalfa produced a pound of crop for each 495 lb. of rainfall. On land receiving from 12 to 30 in. of irrigation, the average production was at the rate of 1 lb. of crop for each 585 lb. of total rainfall and irrigation. Even if all moisture is assumed to have been used as transpiration in the fields, the transpiration ratio is less than that found in the tanks. Field use included evaporation and perhaps some deep percolation.

SUMMARY

The conditions affecting surface waste, deep percolation, soil-moisture evaporation, and transpiration have been discussed with illustrations of the amounts of each item under various conditions. As all of the water delivered to land is accounted for by these four methods of disposal, their usual limits can be expressed as a percentage of the total delivery. As the proportions of the total supply represented by each item vary widely

with the soil texture and other conditions of practice, only general limits can be defined. The following table indicates the general variations to be expected:

DISPOSAL OF IRRIGATION WATER DELIVERED TO LAND IN PERCENTAGE OF THE TOTAL DELIVERY

Disposal	Usual minimum	General average	Usual maximum
Surface waste	0 to 3	5	10 to 20
Deep percolation	5 to 15	25 to 40	50 to 65
Soil-moisture evaporation	5 to 10	10 to 15	15 to 20
Remaining for transpiration	70 to 80	40 to 60	20 to 35

On any given area, conditions are not usually favorable to either all minimum or all maximum rates of loss. On coarse soils for which it is difficult to prevent excessive deep percolation, surface waste is easily prevented and soil-moisture evaporation is less than average. On heavy soils on steep slopes where waste and evaporation may be large, percolation loss may be very small. For the best conditions of practice, plants do not secure more than two-thirds to three-fourths of the water applied. For much practice with unfavorable soil conditions or with careless application of water, crops may secure less than one-third of the total depth delivered to the land. As a general average, it is doubtful if over one-half of the water delivered from irrigation systems is made available to the crops and is used for transpiration.

While in many localities present average losses are large and can be reduced with proper methods of irrigation, the expense of their reduction in some cases may exceed the present value of the water that would be saved. Where the losses are excessive, usually the best crop results are not secured and it will pay to improve the methods used and reduce the losses to reasonable amounts.

In addition to the losses of water delivered to the field, there are conveyance losses by seepage from the canals carrying the water to the land. These losses vary with the size and length of the canals and the character of the soil and construction used. For pumping from wells on the farm, this loss occurs only in the farm system and may not exceed 5 per cent of the supply. For canal systems the conveyance loss varies generally from 10 to 40 per

cent of the amount diverted. Such conveyance losses still further reduce the proportion of the water supply diverted that is used as transpiration by the crops.

References

1. Bark, D. H.: Experiments on the Economical Use of Irrigation Water in Idaho, *U. S. Dept. Agr. Bull.* 339, 1916.
2. Mathews, O. R.: Water Penetration in the Gumbo Soils of the Belle Fourche Reclamation Project, *U. S. Dept. Agr. Bull.* 447, 1916.
3. Bark, D. H.: Losses and Waste of Water, *Ninth Biennial Rep. State Engineer of Idaho*, 1912.
4. Steward, W. G.: Duty of Water Investigations on the Boise Project, *Rep. Boise Conference of Operating Engineers*, 1911.
5. Adams, Frank, and Others: Investigations of the Economical Duty of Water for Alfalfa in Sacramento Valley, Calif., *State Dept. Eng. Bull.* 3, 1917.
6. Dean, H. K.: Work of the Umatilla Field Station in 1923, 1924, and 1925, *U. S. Dept. of Agr. Circ.* 422, 1927.
7. Widtsoe, J. A., and W. W. McLaughlin: The Movement of Water in Irrigated Soils, *Utah Agr. Exp. Sta. Bull.* 115, 1912.
8. Sleight, R. B.: Evaporation from the Surfaces of Water and River Bed Materials, *Jour. Agr. Research*, vol. I, No. 5, 1917.
9. Shaw, C. F., and A. Smith: Maximum Height of Capillary Rise Starting with Soil at Capillary Saturation, *California Agr. Exp. Sta., Hilgardia*, vol. 2, No. 11, 1927.
10. Shaw, C. F.: When the Soil Mulch Conserves Moisture, *Jour. Am. Soc. Agron.*, vol. 21, No. 12, 1929.
11. Fortier, S., and S. H. Beckett: Evaporation from Irrigated Soils, *U. S. Dept. Agric., O. E. S. Bull.* 248, 1912.
12. Veihmeyer, F. J.: Some Factors Affecting the Irrigation Requirements of Deciduous Orchards, *California Agr. Exp. Sta., Hilgardia*, vol. 2, No. 6, 1927.
13. Kiesselbach, T. A.: Transpiration as a Factor in Crop Production, *Nebraska Agr. Exp. Sta. Research Bull.* 6, 1916.
14. Briggs, L. J., and H. L. Shantz: Daily Transpiration during the Normal Growth Period and Its Correlation with the Weather, *Jour. Agr. Research*, vol. 7, No. 4, 1916.
15. Shantz, H. L., and L. N. Piemeisel: Water Requirements of Plants at Akron, Colo., *Jour. Agr. Research*, vol. 34, p. 1093, 1927.
16. Fortier, S.: "Duty of Water in Irrigation," International Engineering Congress, Waterways and Irrigation, p. 458, 1915.
17. Fortier, S.: Evaporation Losses in Irrigation and Water Requirements of Crops, *U. S. Dept. Agric., O. E. S. Bull.* 177, 1907.

CHAPTER IV

WATER REQUIREMENTS OF IRRIGATED CROPS

The water requirements of irrigated crops vary widely owing to the great diversity of conditions under which irrigation is practiced. It is neither practicable nor essential to attempt a detailed discussion of the extent to which all such variations in local conditions react on the amount of water used. For any individual farm or canal system, the actual practice is the result of the experience acquired in handling water under the combined effect of all local factors. Such experience is an essential element in judging the economy of any local practice. However, in purchasing new lands, the prospective purchasers need to reach a conclusion on the adequacy of the available water supply to meet the demands of the lands before such local experience is available to the purchaser. Similar conclusions in advance of actual use are required in making the plans for new irrigation systems. Frequently questions regarding the extent of use required arise in connection with the determinations of the title to the water right and its administration under the systems of title to the use of water followed by the western states.

In this and the following chapter, the factors affecting the use of irrigation water, with sufficient illustrations from practice and experiment to indicate the amounts of use under typical conditions, are discussed. No attempt is made to present a complete inventory of use under all of the wide variety of conditions encountered in irrigation practice.

DEFINITIONS

Different terms are used to express the relationship of the amount of water used and the area of land irrigated. One of the more common terms is "the duty of water." The terms "water requirements" and "water use" are becoming more generally used and are the expressions more frequently employed in the following discussions.

The water requirement of any irrigated crop is the amount of water required for the production of the crop. In practice, this

term is used to define the amount of water applied by irrigation. The water requirement in irrigation practice, as the term is generally used, does not include the moisture that may be obtained from rainfall or by sub-irrigation. The water requirement may be expressed numerically either in terms of the depth of water used on the land in a given time period or in terms of the area which a given rate of flow will supply. The water requirement may be large, indicating a large use of water, or small, indicating the opposite. Various descriptive terms may be used to indicate different classes of practice, such as the "economic water requirement" where the use represents the most economic results from the amount of water used.

The term duty of water similarly represents the relation between the area of land served and the quantity of water used. However, the term is somewhat confusing in its applications as a high duty of water represents a small amount of use and a low duty represents a large use. The term water requirement is free from this confusion and is considered preferable, although the term duty of water has been extensively used in past literature on irrigation practice and is still generally employed.

As the water requirement represents a ratio between the water used and the lands served, different numerical values are obtained dependent on the point at which the water may be measured. Where the water is measured at the intake of the canal system and represents the gross supply, the term "gross water requirement" is used. Where the water is measured at the delivery to the farm and represents the net delivery, after deduction of conveyance losses in the canal system, the term "net water requirement" is used. In some cases the water will be measured at the head of the laterals, giving an intermediate value of the water requirement between the gross and the net use.

All of these values of the water requirement are needed in the planning and operation of canal systems. The gross requirement represents the total supply that needs to be secured for any system. The net requirement represents the needs for plant transpiration, percolation, soil-moisture evaporation, and surface waste. Where the water requirement of any of the crops it is desired to grow can be fully supplied, the landowner can select his crops free from limitations of water supply. Where such a supply cannot be furnished, crops will need to be adjusted to the supply.

The actual water use under any system represents the character of the local practice. This may be either economical or wasteful. The correct water requirement for maximum yield per acre is the quantity of water which it is necessary to use to produce such maximum yields when the losses of water by percolation, evaporation, and waste have been eliminated to the extent that is practicable with skillful methods of irrigation and crop practices. The water requirement for maximum economical yield from a limited water supply is that quantity of water which will give the maximum total net returns from the available water supply and is dependent on the value of the water and the land, the cost of irrigating and producing the crop, and the value of the crop. The net water use merely represents the amount of water which is used under the local conditions of water supply and judgment and skill in applying water. Where water is cheap and abundant throughout the irrigation season, the actual use will often exceed the water requirement for economic practice, as the conditions do not require care in the handling of water. For the more usual conditions of the arid regions where water is scarce and valuable, the actual use tends to approach the correct water requirement for maximum economic yield. Closer approach toward such economic yields takes place gradually at such rate as cost conditions relating to the crop production may justify. However, in common with other economic matters, actual improvements in practice tend to lag somewhat behind the time when their use would be profitable.

UNITS OF MEASUREMENT OF WATER

In order to express the water requirements in numerical terms, a knowledge of the units of measurement of irrigation water is necessary. The units of measurement may be divided into two classes: first, those expressing a definite volume of water and generally used to state quantities of water at rest and, second, those expressing a rate of flow or discharge.

The more usual units of volume employed in irrigation are the gallon, the cubic foot, the acre-inch, and the acre-foot. The gallon and cubic foot are suited to use for small volumes of water but are seldom convenient for use in irrigation. The larger unit, the acre-foot, is used with large volumes of water, such as for the capacity of storage reservoirs. It is also used to express the water use in terms of the depth of water on the land in the form of

acre-feet per acre. An acre-foot represents a volume of water equivalent to a depth of 1 ft. on an area of 1 acre and is equal to 43,560 cu. ft. The acre-inch is equal to $\frac{1}{12}$ acre-foot or 1-in. depth of water on an area of 1 acre.

The units of rate of flow commonly used in irrigation are the cubic foot per second and the miner's inch. The former term is more generally used for larger rates of flow and the latter for the smaller.

Cubic Feet per Second.—The cubic foot per second, commonly abbreviated to second-foot and in India to cu-sec, is a rate of flow which produces a cubic foot of water each second. It is a volume of 1 cu. ft. of water moving at a velocity of 1 lineal foot per second; for instance, a flume 12 in. wide carrying a depth of water of 12 in., and placed on such a grade as to give a velocity to the water of 1 lineal foot each second, produces a flow of 1 cu. ft. per second. In any case the cross-sectional area of the water channel in square feet multiplied by the average velocity in feet per second will give the discharge in cubic feet per second.

Miner's Inch.—The miner's inch is the quantity of water which discharges freely into the air through each square inch of opening when the water stands at a prescribed constant height above the center of the opening. The number of miner's inches is equal to the area of the opening in square inches. For discharge without submergence the discharge through each square inch of opening is controlled by the height of the water level above the center of the opening, but it is also affected by the shape of the orifice and other elements which influence the flow of water through orifices. The term is generally associated with a certain method of measuring water, and unless the same method is used variable results may be obtained.

The miner's inch method of measurement was developed in the early mining days of the west to meet the need for a device that would enable the quantity of water flowing to be determined from lineal dimensions alone. Discharge through orifices varies as the square root of the head or pressure of the water on the opening. To avoid extracting the square root of the head on orifices in order to determine the discharge, the head was made constant and the flow through 1 sq. in. of opening was made the unit of measurement. The standardized head varied in different areas and the legal value of the miner's inch now varies in different states. In Arizona, Montana, and Oregon the legal value is

$\frac{1}{40}$ sec.-ft. which is obtained with 6-in. pressure on the center of the opening. In Idaho, Nebraska, Nevada, New Mexico, North and South Dakota, and Utah the legal value is $\frac{1}{50}$ sec.-ft. which is obtained with a 4-in. pressure. While the method of measurement and dimensions of the structure were prescribed in the earlier statutes of some of the states, the more usual present definition is in terms of the number of miner's inches equaling 1 sec.-ft. which in effect makes the second-foot the legal unit of measurement. In California the legal value is based on 6-in. pressure, but the more usual practice uses a 4-in. pressure. In Colorado the method prescribed gives values varying from 35 to 43 miner's inches to the second-foot for different conditions of use, with a commonly accepted equivalent of 38.4. In British Columbia 35.7 miner's inches equal 1 sec.-ft.

Although the miner's inch unit is open to variations in its value and is sometimes confused with the cross-sectional area in square inches of flow in channels, flumes, and pipes, it has the advantage that the flow, being directly proportional to the cross-sectional area of the orifice, is more readily understood by the users than the term "second-feet." It is also a more convenient size of unit for smaller flows involving fractional values if expressed in second-feet. It is in common usage where the streams handled are less than 2 or 3 sec.-ft., although the methods of measurement now used may have no relation to the old forms of miner's inch box.

Another unit sometimes used is the irrigation stream or head of water. This refers to the usual rate of flow delivered under a given canal system and is not a unit of measurement, as the size of stream varies with the method of applying water to the land and other elements of local practice. The size of head delivered may vary from a few miner's inches or a fraction of a cubic foot per second with furrow irrigation to 15 or 20 sec.-ft. under flooding in checks as practiced in parts of California and Arizona.

METHODS OF EXPRESSING WATER REQUIREMENTS

Water requirements may be expressed in two ways:

1. In number of acres irrigated by a flow of water, usually 1 sec.-ft. or 1 miner's inch, for a stated period of time during the irrigation season.

2. In number of acre-feet or acre-inches per acre, which is equivalent to stating the depth of water applied on the land in feet or in inches.

In the first form of expression the time must be specified in order to define a given volume of water. In general, it is not a constant value throughout the irrigation season but varies with the needs of the crops and demands on the water supply. It is the form of expression best adapted when the volume of water is stated as a rate of flow, such as when considering the discharge or carrying capacity of canals.

The second form of expression avoids any misunderstanding regarding the volume of water applied. One form of expression can be easily converted into the other if the time during which the rate of flow continues is known.

RELATION BETWEEN UNITS OF MEASUREMENT OF RATE OF FLOW AND UNITS OF MEASUREMENT OF VOLUME

The cubic foot per second or second-foot and the miner's inch indicate only a rate of flow, and to specify a fixed volume of water it is necessary to state the time or duration of flow. For instance, a continuous flow of 1 cu. ft. per second will give in one 24-hr. day as many cubic feet as there are seconds in that time or 86,400 cu. ft., which is equal to 1.983 acre-feet. For practical purposes it is sufficiently accurate to assume that a flow of 1 cu. ft. per second will produce 2 acre-feet of water in 24 hr., or 1 acre-inch per hour. To convert measurement from one unit into another, the following equivalents are useful:

1 cu. ft. = 7.50 gal. (7.48).

1 acre-foot = 43,560 cu. ft. = 325,850 gal.

1 sec.-ft. = 7.50 gal. per second = 450 gal. per minute.

1 sec.-ft. in 24 hr. gives nearly 2 acre-feet (1.983).

1 sec.-ft. in 1 hr. gives nearly 1 acre-inch.

1 sec.-ft. is equivalent to 40 miner's inches controlled by a 6-in. pressure head.

1 sec.-ft. is equivalent to 50 miner's inches controlled by a 4-in. pressure head.

When 1 miner's inch is equivalent to $\frac{1}{40}$ sec.-ft., it will give 11.25 gal. per minute, or nearly $\frac{9}{10}$ acre-inch, in 24 hr., or 17.37 acre-inches in a month of 30 days.

When 1 miner's inch is equivalent to $\frac{1}{50}$ sec.-ft., it will give 9 gal. per minute, or nearly $\frac{1}{2}$ acre-inch in 24 hr. ($\frac{48}{100}$), or 14 acre-inches in a month of 30 days.

PRINCIPAL FACTORS AFFECTING GROSS AND NET WATER REQUIREMENTS

The gross water requirement is dependent on the net requirement and on the conveyance losses. Among the factors which affect the net requirement are

1. The kind and diversification of crops. Some crops require more water than others; use for alfalfa exceeds that for deciduous orchards and full-bearing orchards exceed the use for young trees. The growing of a single kind of crop usually results in a comparatively short period of maximum demand with a large requirement during this period. The growing of a variety of crops which have different requirements and periods of maximum use will result in a more uniform demand. As the crops first grown are frequently mainly forage types, later diversity of crops usually results in a smaller average use per acre.

2. The preparation of the land, method of application of the water, and skill of the irrigator. Poor preparation of the land causes excess application on the low areas and uneven distribution. Irrigation through furrows of excessive length or by flooding over too great a distance with small heads causes excessive deep percolation at the upper ends of the runs. Rotation in delivery with the use of large irrigating heads for short periods of time usually decreases the losses and the amounts used. Careless handling of water will often result in an accumulation of excess water and waste at the lower ends of fields or furrows. Care in division of water to furrows is required to secure even distribution. Deep furrows expose less soil and water to evaporation.

3. The time and frequency of cultivation. Cultivation reduces loss of moisture through weeds and evaporation from the soil where the ground water is within capillary reach of the ground surface.

4. The length of time irrigation has been practiced. The first leveling of land in new projects is not so well adapted to local conditions or so carefully done as the later releveling in crop rotations where local experience has become available. The rise of the ground water which usually results from irrigation

may enable some lands to secure at least part of their supply from sub-irrigation. Such rise may also waterlog and render unproductive part of the area. In the earlier years of operation, the water supply is usually ample for the smaller area irrigated and deliveries may be more liberal than can be maintained when the full area comes into use.

5. Climatic factors. Precipitation, temperature, humidity, and wind movement all have some effect. The amount and distribution of rainfall are important. Rainfall or snow during the winter may be retained in the soil up to its field-moisture capacity and be available to deep-rooted crops during the growing season, thus decreasing the amount of irrigation required. Light rains in the summer do not enable irrigation to be reduced. Transpiration and soil-moisture evaporation are increased by high temperature, wind movement, and low humidity.

6. Length of the growing season. Where the growing season is long, the amount of irrigation required is larger than for a short growing season. The rate of use, however, is not directly proportional to the length of growing season as, even in areas where crops may be grown throughout the year, much of the land will not be in continuous use during the full year.

7. Character of the soil and subsoil. A coarse-textured soil is difficult to handle without large percolation losses. Hardpan or other impervious soil strata may reduce the water used on coarse soils, if such heavier subsoils occur at a depth of 4 to 6 ft., owing to reduction in percolation. Similar strata may increase the use if they occur so close to the surface that the shallow depth of soil increases the frequency of irrigation required. While coarse soils may require the use of larger amounts of water in order to meet losses, actual moisture consumption by crops is not materially different for similar yields on heavy and coarse soils.

8. The value of the water and method of payment. A high cost of water tends to result in a more economical use. For many systems the charge for water is a uniform rate per acre for any amount of use up to the maximum which the system will supply. For such a basis of charges, it is a human tendency to use all the water obtainable. Where the charge is based on the amount of water used, there is an incentive toward more careful use. Where additional water costs less than the additional labor or other costs required to reduce the amount of water used, charges based on the amount of water used do not materially affect the irrigation prac-

tice. Many early court decrees granted rights to the use of water in excess of actual needs. Under such systems, excessive use frequently occurred with resulting injury to the lands due to the resulting waterlogging and alkali injury. Present practice in the determination of beneficial use in water-right adjudications is based much more nearly on the actual needs of the lands served.

RELATION BETWEEN AMOUNT OF WATER USED AND RESULTING YIELD

In irrigated areas it is generally found that the yield increases with an increase in the amount of water applied for the smaller to moderate amounts of irrigation and that further increase in the water used results in a reduced rate of crop increase and in an actual decrease in yield if the use is carried to excess. The amount of water resulting in maximum yield varies with the crop and other factors. Some crops are more sensitive to excess use and show a more rapid reduction in yield with such use.

In areas where the precipitation is insufficient for any crop production without irrigation, the yield curve rises more rapidly with the amount of irrigation than in areas where irrigation is supplemental to the rainfall. Similar amounts of maximum yields would be secured in arid and semi-arid areas in which other factors are comparable.

The most profitable yield is usually somewhat less than the maximum as the values of the last increments of yield are not equal to the cost of securing them. The most profitable use is not a fixed amount for any crop and locality, as it varies with the fluctuations in cost of production and the price of the crop. In much practice the most profitable amount of irrigation is represented by an amount of use equal to two-thirds to three-fourths of that producing maximum yields.

EXPERIMENTAL METHODS

The relation between the amount of water used and the resulting yield is not fixed. A given amount of irrigation may produce widely varying yields when applied to soils of variable fertility. For the same soil the yield does not vary directly with the amount of water applied. Excessive use of water may result in decreased yields.

Many experiments have been made to determine the effect of varying the amount of water used on the resulting yields. Repre-

sentative results for different crops are presented later in this chapter. In order to secure dependable results, such experiments should be made under conditions where all other factors except the water used are uniform. This is difficult to secure under general field conditions, so that many experiments have been made on small areas under more close control or even in tanks under relatively complete control. While such control has advantages from the experimental point of view, it raises questions regarding the interpretation of the results in terms of field practice that may more than balance the experimental advantages.

Experiments on the effect of irrigation on the yield of crops usually consist of trials with different amounts of irrigation covering a range from inadequate moisture supply to an excessive use in order that the most desirable use may be determined from all the results obtained. Considerable variation in the results of individual observations are to be expected in such work. This is usually recognized and the experiments conducted in multiples. It is also recognized that the variations in climatic factors will affect the results and the observations are usually conducted over a series of years in order that the period may include an average of the climatic conditions.

In order to avoid soil variations and still permit enough separate areas for the number of observations desired, many experiments have been made on plats of from $\frac{1}{20}$ to 1 acre in area. This gives advantages in control as water may be more evenly spread over such small areas than is practicable under general field conditions. Other observations have been conducted on selected fields of farms where 3 to 10 acres may be used in each test. Such work has the advantage of being conducted under conditions similar to those confronting the usual irrigator but has the disadvantage of the greater variation in the stand of the crop and the soil. The results of such work, while more convincing to the landowners, generally show wider variations in the relationship of yield to the amount of water used and a larger number of observations are needed to derive dependable conclusions.

Nearly all experiments on the use of water have been made on lands having the water table at a sufficient depth so that subirrigation does not occur. Such areas have been selected so as to avoid the complications that would be caused by the water obtained by the crops from the ground water, as the amount of such use cannot be measured under field conditions. The amount

of surface application required on well-drained lands is larger than is needed on lands having ground water within 6 ft. of the ground surface. Consequently the results of experiments on well-drained land indicate the need of larger average amounts of use than would be needed on systems where much of the land receives part of its supply by sub-irrigation or for areas having smaller average yields. As it is a usual experience for the water table to rise following irrigation under much of the land irrigated, such sub-irrigation may reduce the amount of water needed for the system below that indicated from experiments on well-drained areas.

FORAGE CROPS

Irrigated forage crops include alfalfa, clover, timothy, and various native grasses. Alfalfa is the most extensively grown irrigated forage crop in the United States. Forage may be cut for hay, pastured, or used for seed production.

With forage crops, practically all of the aboveground portions of the plant are included in the commercial yield. Differences in quality of yield due to differences in cultural practice are less marked than with many other crops. Consequently forage-crop practice is directed mainly toward securing maximum growth of the plants and the amount of water used is larger than for other types of usual crops. Forage crops are also less sensitive to either overuse or drought than many other crops.

Alfalfa is deep-rooted, grasses are generally shallow-rooted. While the total depth of irrigation per season under similar soil and climatic conditions is generally similar for alfalfa and the grasses, the shallow-rooted types of forage crops require more frequent and lighter individual irrigations.

As alfalfa is the most extensive and the most carefully handled of the forage crops, there is a larger amount of experimental data available regarding its irrigation than for the other types.

ALFALFA

Alfalfa is grown throughout the irrigated areas in the United States. In the southwest, growth may continue during all months of the year and six to eight cuttings may be obtained. In northern areas or at the higher altitudes, the shorter growing season may result in only two or three cuttings being secured. In localities where only two cuttings can be obtained, the short-

ness of the season also limits the choice of other crops that may be grown. In three-crop areas, the third crop has a smaller yield and may be pastured rather than cut for hay. In the areas of shorter season, clover, timothy, and native grasses tend to replace alfalfa for forage crops.

The stage of growth at which alfalfa may be cut varies with climatic conditions. In long-season areas the crop is usually cut when about one-tenth in bloom; in short-season areas where an added cutting cannot be secured by early cutting, much alfalfa reaches full bloom. Yield on good stands with early cuttings may average 1 to 1½ tons per acre per crop; for crops cut when more fully in bloom the average may be 1½ to 2 tons per cutting. Average yields for large areas where fields of all conditions are included are less than these amounts. In areas where temperature conditions permit growth throughout the year, it is usual to suspend irrigation during part of the hotter summer months; such resting results in longer life for the stand before reseeding is needed.

The need for irrigation is shown by alfalfa by a darkening of the green color of the growth. This change is readily discernible in a field where portions are becoming dry. Further drying results in permanent wilting from which the growing crop may not recover. Such temporary moisture deficiency does not destroy the root system. Renewal of the moisture supply after an essential shortage starts the growth of the shoots for the next crop rather than reviving the wilted growth. The growth of alfalfa which has reached the dark-green stage is not affected if irrigation is applied before wilting occurs.

In planting alfalfa, irrigation should be applied before seeding unless the soil contains sufficient moisture for germination and initial growth. The soil moisture at the time of seeding should carry the crop on all except the coarser soils until it is 4 to 6 in. high and can be irrigated without injury. Coarse soils or those that blow will require more frequent early irrigations. It has been thought that too frequent early irrigations result in less depth of root growth but experimental data lend little support to this view. If weed growth interferes with the young alfalfa, clipping 4 in. high will not injure the crop.

Seeding in the spring is usual. In order to avoid loss of return during the first year, nurse crops of grain are used in some areas. The grain matures early enough to avoid injury to the alfalfa.

In areas of longer growing seasons some alfalfa production may be secured during the first season and nurse crops are not usual. Fall seeding after removal of an annual crop may be used in areas having mild winters.

Where a seed crop is grown, irrigation should be restricted in order to obtain a good setting of seed. In areas producing three crops of hay, the first or second crop may be left for seed. For seed crops the water requirement is about one-half that required for hay production.

Alfalfa used for pasture requires a similar amount of irrigation per season to that used for hay. Pasturing alfalfa tends to shorten the life of the stand, particularly if it is pastured while wet. Many alfalfa fields where the stand has become thin and the hay yield has declined are pastured for one or more years before reseeding. Pastures are usually irrigated at from 7- to 14-day periods owing to the shallow roots of the grasses which come in with the alfalfa when pastured; the individual irrigations should be lighter than for the less frequent irrigations used where the crop is cut for hay.

Total Use per Season.—Unless waterlogging, alkali, or other directly injurious conditions are present, alfalfa is not so susceptible to injury by excessive use of water as other types of crops. For the earlier years after planting, yields may tend to increase with increased amounts of irrigation. The rate of such increase in yield with increase in use is generally small and the continuation of such large use usually results in a shorter period of well-maintained yield than for more moderate amounts of use.

Results of experiments on the effect of variations in the total amount of use per season on the yield are available from a number of states. Typical results are shown in the following tables and diagrams. Except where noted, these experiments were all conducted on field plats of less than 1 acre in area where the water was evenly distributed. Surface waste was prevented or has been deducted from the amounts of use shown. The water used includes the soil-moisture evaporation and such deep percolation as may have occurred, as well as the transpiration by the crops. In all cases ground water was at too great a depth to be a factor in the moisture supply of the crop. The use of water shown represents the irrigation use alone unless otherwise stated.

Figure 27 gives the results of several series of experiments on the relationship of the total amount of irrigation and the resulting

yield. The results shown in Curve 1 were obtained in Alberta, Canada,[1] on a silt loam soil. The rainfall during the irrigation season, which averaged about 6 in., is included in the use of water. The observations extended for 4 years. The results shown are the mean for stands two to five years old. For amounts of use from 2 to 3.25 acre-feet per acre the yields on four- and five-year-old stands exceeded those on two- and three-year-old stands. For less and for greater depths of irrigation the yield on four- and

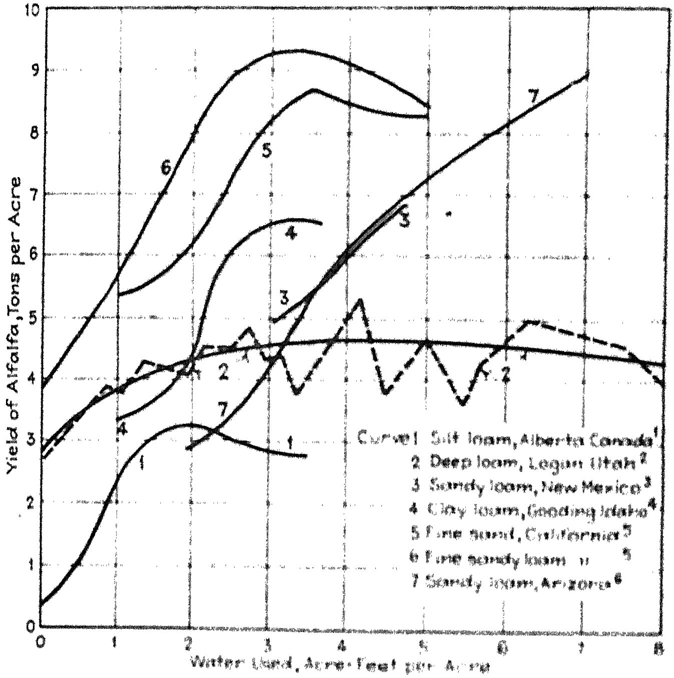


FIG. 27.—Results of experiments on the amount of water used and the resulting yields for alfalfa. (*Adapted from Snelson,[1] Harris,[2] Thompson and Burrows,[3] Welch,[4] Beckett and Huberty,[5] Marr.[6]*)

five-year stands had declined below those for stands two and three years old.

Curve 2 represents the results of 176 tests extending over 14 years on 0.04-acre plots at Logan, Utah.[2] The soil is a deep uniform loam. The dotted line connects the actual results for the different amounts of use; the full line represents the generalized results. The variation in individual observations is typical of the results of such experiments, as the yield is affected by other

factors than the total seasonal amount of irrigation. The average annual rainfall at Logan of 16.2 in. is not included in the use of water shown but accounts for the yields obtained with no irrigation.

Curve 3 represents results in New Mexico[3] on a sandy loam soil. These experiments were not extended to the point of reduced yields. The average rainfall of 4.4 in. from April to September

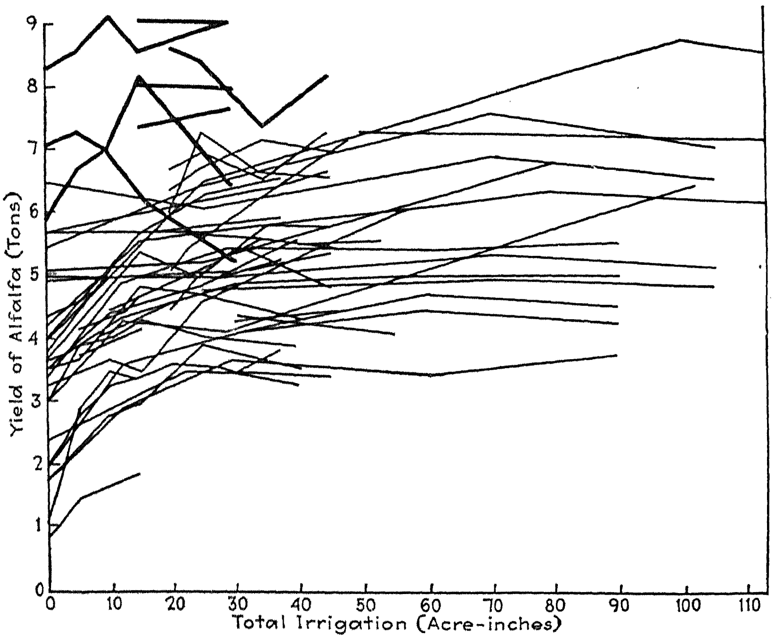


FIG. 28.—Curves showing the effect of different quantities of irrigation water on the yield of alfalfa hay. (*Pittman and Stewart.*[7]) Each line represents a single comparable series, all results in each series being obtained in a single season. Different plat series for the same year, or the same plat series in another year, are represented by separate curves. The heavy curves in the upper left corner of the chart were obtained from similar applications of water on a different field which for 20 years had been heavily manured.

for the 4 years covered by the observations is not included in the water used. Curve 4 represents 4 years' results at Gooding, Idaho,[4] on medium clay loam soils.

Curve 5 gives the results of 3 years' records on sandy land with heavier subsoil at 5 to 6 ft. at Delhi, Calif.[5] Curve 6 gives similar results for 6 years' work on fine sandy loam soils at Davis, Calif.[5] The mean annual rainfall during these experiments of 11.7 in. at Delhi and 17 in. at Davis, occurring in the winter and early

spring months, is not included in the water used but is the cause of the amount of yield shown for no irrigation. At Davis the first one or two cuttings of the season may not require irrigation.

Curve 7 represents results for one year's results on small plats at Higley, Ariz.,[6] on sandy loam soils. Large use of water for high yields is shown. The greater use for similar yields as shown by Curve 7 than those by Curves 5 and 6 is due to the longer and warmer season and the smaller rainfall at Higley as compared with Delhi and Davis.

Figure 27 shows the generally smaller yields in areas of shorter season. In general, yields increase with the amount of water used up to a point where additional irrigation becomes harmful and the yield is reduced. The amount of use required for economical or for maximum yield varies with the soil and climatic factors.

Results of experiments at the Utah Agricultural Experiment Station[7] covering different series of observations are shown in Fig. 28. While these results illustrate clearly the wide variations that may occur in the amount of the yield, the individual series show in general a similar type of variation in yield with different amounts of irrigation. For the conditions of these experiments the yield increases slowly with an increase in the water used up to amounts of use of 20- to 30-in. depth per season. Larger amounts of use caused little increase in yield.

In Table X are shown some details of the results obtained at Davis, Calif.,[5,10] which are plotted in Curve 6 of Fig. 27.

TABLE X.—SUMMARY OF ALFALFA EXPERIMENTS AT DAVIS, CALIF., 1910–1915[10]

Number of irriga-tions	Depth per irrigation, inches	Total depth of irrigation per season, inches	Average yield per season, tons per acre	Average value of crop per acre	Average cost of production per acre	Average net return per acre
None	....	..	3.88	$27.16	$ 8.73	$18.43
2	6	12	5.63	39.41	15.37	24.04
3	6	18	6.80	47.60	19.35	28.25
4	6	24	7.92	55.44	23.22	32.22
4	7½	30	8.98	62.86	26.45	36.41
4	9	36	9.27	64.89	27.96	36.93
4	12	48	9.02	63.14	29.10	34.04
4	15	60	8.42	58.94	29.44	29.50

The annual precipitation for the 6-year period averaged 17.0 in., 3 years being below normal and 3 above. The average market value of alfalfa in the stack for this period was $7 per ton. The labor cost of production was $2.25 per ton, the cost of water $1.70 per acre-foot, and the labor cost per acre per irrigation $0.50. Six cuttings were obtained. No fixed charges are included in the cost of production shown. The average net returns shown in the last column represent the amounts available to meet fixed charges and profits.

At the end of the experiment it was found that the best stands were on the areas receiving 30-in. depth of irrigation per season, the alfalfa receiving the largest amounts of water being largely replaced by grass and that receiving limited amounts of water also showing much thinning out. It was concluded that, for the conditions of these experiments, a use of 30-in. depth of irrigation represented the most economical practice. From similar experiments at Delhi, Calif.,[5] in the San Joaquin Valley, it was concluded that 36-in. depth represented economical use there, the increase in recommended depth of irrigation at Delhi over that at Davis being about equal to the difference in mean annual rainfall.

These results at Davis and Delhi are applicable to lands where ground water is too deep to affect irrigation use. In adjacent areas under the Turlock and the Modesto Irrigation Districts good yields have been obtained on lands having ground water at depths of about 5 ft. with depths of irrigation of 2 ft. per season.

Results of measurements on 42 farms having an average area of 52 acres extending over three seasons in the Salt River Valley, Ariz.,[6] are shown in Fig. 29. The average curve shown does not differ materially from Curve 7 of Fig. 27, which represents small plats under the same soil and climatic conditions. The individual results shown in Fig. 29 vary more widely than those obtained on small plats. Such larger variations are due to the less complete control of the crop and water conditions on the larger areas. The point of decrease in yield with increase in use had not been reached for the amounts of use shown in Fig. 29.

Number and Frequency of Irrigations.—The details of the distribution of the individual applications of water on alfalfa vary with the soil conditions and the crop practice followed. As long as the soil moisture does not reach the wilting percentage, the frequency and amount of each irrigation have less effect on the yield than for most other types of crop.

As alfalfa is deep-rooted, it is able to utilize nearly the full moisture-storage capacity of the soil to depths of 6 to 8 ft. with some use to greater depths. As shown in Chap. II, the larger part of the feeding roots are in the upper 4 ft. of soil. The crop will usually indicate the need for irrigation if the upper 4 or 5 ft. of soil becomes dry, even though there may be some moisture available at lower depths. The deeper roots do not secure such deeper moisture at a sufficiently rapid rate to meet the crop needs.

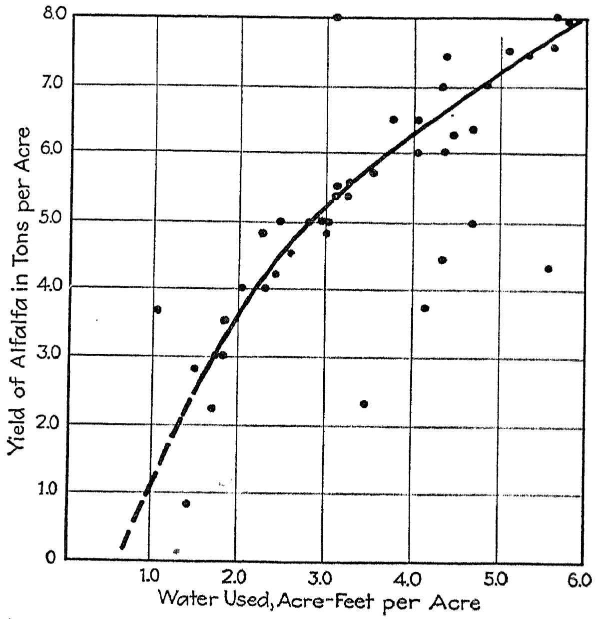


FIG. 29.—Results of measurements of the water used and the yield of alfalfa on 42 farms in the Salt River Valley, Arizona. (*Marr.*[6])

For alfalfa cut in early bloom, one irrigation per cutting may be sufficient on deep soils of medium texture. For coarse soils or for medium soils of shallow depth two or three irrigations per cutting may be required. For soils of heavy texture, where only small depths of penetration can be secured at each irrigation, two or three irrigations per cutting may also be required. These conclusions are illustrated by the following experiments.

Measurements with constant seasonal depth but with varying numbers and depths of irrigation have been made in California covering a wider range of practice than is usual in this type of experiment. At Davis[5] seasonal depths of 30 in. were applied in

from 2 to 12 irrigations. The soil is a loam to a depth of 18 to 20 ft., having a good moisture holding capacity. Ground water was at depths of 14 ft. or more. The rainfall occurring during the winter and spring is sufficient to meet the moisture needs of the first one or two cuttings of the season. Three or four repetitions of each depth of irrigation were used for 8 years on plots about ⅔ acre in area. All plots gave good average yields. The lowest yield resulted from four irrigations applied once per cutting after the first cutting. The differences in yield were not large as shown in Table XI.

TABLE XI.—EFFECT OF VARIATIONS IN IRRIGATION ON YIELD OF ALFALFA AT DAVIS, CALIF.[5]

Number of irrigations	Depth of each irrigation, inches	Average yield, tons per acre
2	15.	8.24
3	10.	8.41
4	7.5	7.57
6	5.	8.72
8	3.75	8.79
12	2.5	9.42

The effect of varying numbers of irrigations is shown by results obtained on medium-heavy soils at the Gooding Experiment Station[8] in Idaho in 1911 to 1913. The soil-moisture samples were taken to a depth of 6 ft. Three crops were grown. It was concluded that it was economical to apply three irrigations each to the first and second crops and one or two to the third crop with a

TABLE XII.—EFFECT OF VARIATIONS IN IRRIGATION ON YIELD OF ALFALFA AT GOODING, IDAHO[8]

Number of irrigations	Total acre-feet per acre applied	Yield, tons per acre	Change in soil moisture during season, per cent by weight
3	1.19	3.78	−3.8
4	1.56	4.42	−3.5
6	1.95	5.31	−2.0
7	2.61	5.60	+3.4
10	2.99	6.60	+3.5
11	3.78	6.80	+6.8

total seasonal use of 2.75 acre-feet per acre. Heavier applications increased the soil moisture over that at the beginning of the season, indicating that such use did not deplete the moisture at the end of the season.

Experiments in Washington[9] for 4 years on medium soils gave average yields of 5.37 tons with 14-day frequency of irrigation, 5.61 tons with 21-day, 5.30 tons with 30-day, and 4.50 tons with 42-day frequency. Thirty-day frequency with 7-in. depth per irrigation was recommended.

On a heavy clay loam soil in California,[10] in which both roots and moisture penetrated to only about 2-ft. depth in the soil, 6-in. depth of water applied per cutting gave yields of 4.29 tons per acre when applied in one 6-in. irrigation, 4.42 tons when applied in two 3-in. irrigations, and 5.07 tons when applied in three 2-in. irrigations.

On the sandy soils 4 to 5 ft. in depth on the Umatilla Experiment Station[11] the following results were secured with 4-in. depths of individual irrigations.

Period between irrigations, weeks	Depth of irrigation, acre-feet per acre per season	Yield per acre, tons
1	6.79	6.01
2	4.00	5.55
3	3.06	4.06

It was concluded that the gain in yield from irrigations at weekly intervals did not pay for the added cost and that the 2 weeks' period represented the best practice.

Practice regarding irrigation just before or just after cutting varies with local factors. As long as the soil is not allowed to become too dry, experiments show no essential difference in the yields. The advantages claimed for irrigation before cutting are the smaller evaporation due to shading by the crop and the favorable moisture condition for starting the next crop. The disadvantages are the slower curing of the hay on moist ground and the greater difficulty in distributing water. Irrigation after cutting permits a freer flow over the surface. On steep lands tending to erode or on sandy soils which dry quickly and may have insufficient moisture to start the new crop, irrigation before cutting is generally preferable. For lands where difficulty may exist in

getting the flow over the ground or for heavy soils which dry slowly, irrigation after cutting may be preferable. Irrigation after cutting is also usually preferable where the water contains much silt.

Summary.—The amount of water needed for the irrigation of alfalfa varies with the soil texture, climatic conditions, and depth to ground water. In areas where two or three cuttings are obtained, a use on medium soils of 2 to 3 acre-feet per acre represents usual practice. For the longer growing seasons of the southwest, 3 to 4.5 acre-feet per acre may be needed for medium soils where the rainfall is insufficient to be a material factor in the water supply. In similar long-season areas where winter rainfall may fill the soil-moisture capacity sufficiently to be of direct use to the spring and early summer crops, 2.5 to 3 acre-feet per acre on medium soils is representative of usual practice. Such rates of use include deep percolation and surface waste as well as transpiration and soil-moisture evaporation. Use of the larger amounts stated will generally result in waterlogging of some of the area served.

Soils of heavy texture require more frequent irrigations with smaller depths at each application. The total seasonal use for such soils is similar to the smaller figures stated for medium soils. For coarse-textured porous soils the use may be 1½ to 2 times as large as that on medium soils. Such excess use represents losses by percolation rather than additional plant transpiration.

Where ground water is within reach of the crop roots, the amount of surface irrigation can be reduced by the amount of sub-irrigation secured. Conditions are seldom favorable for complete sub-irrigation and some surface use is generally required. The injury from waterlogging and alkali resulting from efforts to sub-irrigate has exceeded the benefits from reduced irrigation in nearly all areas where such sub-irrigation has been attempted

CEREALS

Wheat, Oats, and Barley.—The commercial return from these crops is dependent on the yield of grain, the value of the straw being relatively small. When grain hay is grown, it is seldom irrigated. Irrigation practice for these cereals is directed toward a maximum yield of grain.

The yield of cereals is dependent on the stand of the crop, the size of head produced by each plant, and the plumpness of the

individual grains. Adequate moisture supply at the times which affect these three stages is essential to good yields.

The stages of growth of cereals are variously defined. The more usual stages include the five leaf, jointing, boot, heading, flowering, milk, and soft and hard dough.

In many areas, sufficient moisture at the time of seeding is available from rainfall. If the soil is dry, it should be irrigated prior to seeding rather than by planting and "irrigating up." The latter practice tends to crust the heavier soils and has been

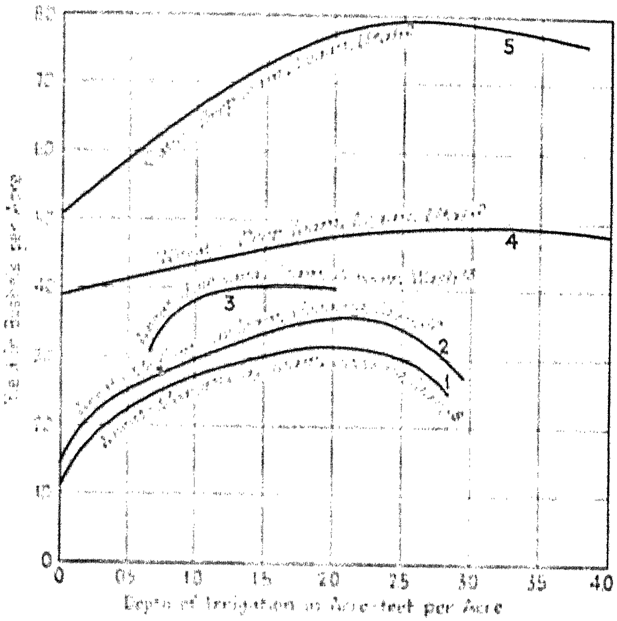


FIG. 30.—Results of experiments on the amount of water used and the resulting yield for wheat and oats. (*Adapted from Harris,*[2] *Welch,*[8,11] *Singleton.*[13])

found to reduce the yields in some tests. During the booting stage the head is forming and an adequate moisture supply is required if heads containing a large number of grains are to be formed. Adequate moisture is also needed during the soft-dough stage to give plump kernels. Irrigation after the soft-dough stage has little effect on the yield.

The relationship between the amount of water used and the resulting yields, based on several series of experiments, is shown in Fig. 30. These results were all obtained on plats of less than 1 acre in size where water was applied under control. The depths

of irrigation are exclusive of rainfall. As rainfall furnishes a sufficient moisture supply in nearly all of these areas to enable some yield to be secured without irrigation, these results show yields with no irrigation of from 30 to 80 per cent of the maximum yield secured with irrigation.

Curve 1 in Fig. 30 represents the results for 4 years on a total of 90 plats on medium clay loam soil at Gooding, Idaho.[8] The annual rainfall for the years covered by the experiments was 9.72 in., of which 3.58 in. occurred during the growing season. The areas used were raw sage-brush land prior to the first year's work. Curve 2 shows the results of a continuation of the same experiments for a total period of 7 years;[12] the mean annual rainfall for the longer period was 9.20 in., of which 2.91 in. occurred during the growing season. The general increase in yield in Curve 2 over that shown in Curve 1 was considered to be due to the improvement in soil fertility.

Curve 3 shows results from 2 years' experiments on medium soils at Prosser, Wash.,[13] with spring wheat. The rainfall for these years was 7 in.

Curves 4 and 5 show results obtained at Logan, Utah,[2] with spring wheat and oats. The mean annual precipitation was 15.5 in. for the years of these experiments, with a favorable distribution for use by grains. The soil is a deep loam. The results for wheat represent 203 tests extending over 13 years, those for oats 78 tests over 6 years. Good yields were secured from rainfall alone, with some increase from moderate amounts of irrigation and a decrease with excessive use.

From the work shown in Curves 1 and 2 it was concluded that for spring wheat on medium soils in southern Idaho the use of over 1.25 acre-feet per acre was not advisable. Winter wheat and barley, which mature earlier and make a larger use of winter rainfall, may not require more than one irrigation with a total use of about 0.75 acre-foot per acre. Oats may use 1.75 acre-feet per acre. At Logan it was also concluded that the use of over 1.25 acre-feet per acre for spring wheat would not be profitable; a somewhat larger use was indicated for oats.

Being an annual crop, cereals are frequently used for lands having an uncertain water supply, as they can be sown quickly if water is available in any year and the loss in idle equipment is relatively small in years of deficient supply. On retentive soils where a part of the moisture requirement may be secured from

rainfall, grain may be grown with one irrigation. Where water is available for only one irrigation, best results have been obtained from an application at the jointing stage. Where two irrigations are given, the early jointing and late boot stages are usually best. For three irrigations, applications at jointing, booting, and soft-dough stages are usual. In some areas where the climate permits winter growth, a grain crop may be secured on retentive soils from one irrigation applied whenever water may be available.

The effect of the amount of precipitation on the need for irrigation of cereals is shown in Table XIII from the results for barley over a period of 6 years at Davis, Calif.[5]

TABLE XIII.—EFFECT OF IRRIGATION ON YIELD OF BARLEY AT DAVIS, CALIF.[5]

Three drier years: average annual rainfall 10.07 in.			Three wetter years: average annual rainfall 23.20 in.		
Number of irrigations	Total depth of irrigations, inches	Average yield of grain, pounds per acre	Number of irrigations	Total depth of irrigation, inches	Average yield of grain, pounds per acre
0	0	840	0	0	1,520
1	6.7	1,636	1	5.2	1,780
2	12.2	2,115	2	7.0	1,810

In this area the precipitation occurs during the winter and spring. The temperatures during the rainy season permit growth of cereals so that the date of maturity is earlier than in areas of more severe winter climate. These results show a large increase of yield from irrigation in dry years but limited benefit in wet years. It was concluded that for these conditions when the annual rainfall equaled or exceeded the normal of 17 in., with normal distribution in time, the increase in the yields did not warrant irrigation. In below-normal years or with unfavorable rainfall distribution with a deficiency in March and April, irrigation, if available, is advisable.

Corn.—Corn is grown under irrigation where temperature conditions permit. In general, its water requirements are similar to those of wheat, oats, and barley. The most critical stage of growth in relation to the moisture supply occurs at tasseling, adequate moisture at this time being essential for good yields.

Results of experiments on the total irrigation use and the yield are shown in Fig. 31 for experiments at Logan, Utah. Curve 1 shows the results for 17 years' work[2] with a total of 118 trials, the full line representing the smoothed relationship and the dotted line connecting the average results for the different depths of use. The departures from the average curve are typical of the results of such experiments, even where many trials are included. Actual crop yields are the result of several other factors in addition to the water supply and a correlation with any single factor does not remove the effect of the other conditions. Curves 2, 3, and 4 are the average results of 13 years' work[14] in which corn was

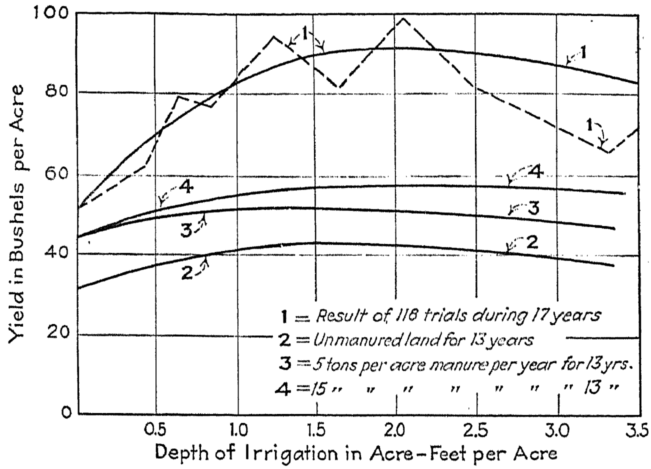


FIG. 31.—Results of experiments on the amount of water used and the yield of corn based on experiments at Logan, Utah. (*Adapted from Harris*,[2] *Pittman*.[14])

grown continuously on the same land, curve 2 being for lands not manured, and Curves 3 and 4 being for land given 5 and 15 tons of manure annually, respectively. The curves are similar in form. The yield without irrigation is about three-fourths the maximum, owing to the favorable distribution of the mean annual rainfall of 16.2 in. at this location. In all cases the experiments showed a reduction in yield at the larger amounts of use.

Results of experiments on the irrigation of corn for ensilage and of grain sorghum at Davis, Calif.,[5] where the normal annual rainfall is 17 in., indicate that for medium soils in years of normal rainfall the net irrigation requirement for full crop production should not exceed 12 in. in depth applied in not more than three

irrigations. In years of below-normal rainfall four irrigations totaling 18 in. in depth may be needed.

Summary.—In general, the water requirement of cereals vary from 1 to 2 acre-feet per acre per season. This is equivalent to about 50 to 60 per cent of the water required for forage crops under similar climatic and soil conditions. In some areas where only one irrigation may be needed to supplement the rainfall, less than 1 acre-foot per acre is required. In areas depending on irrigation for their principal moisture supply, two to three irrigations are usual.

For retentive soils, one irrigation whenever water may be available may enable a grain crop to be produced. Sufficient moisture may be stored in the soil, which with the rainfall during the growing season may meet the crop needs. Winter irrigation for this purpose is practiced in some areas.

RICE

The irrigation of rice differs from that of other crops, in that water is ponded on the land for much of the growing period, the crop being semi-aquatic. Rice is grown in the United States in some of the southern states and in California. Owing to the continued flooding, rice is adapted only to soils of heavy texture or to areas having impervious subsoils. For the 3 to 4½ months of submergence even very slow rates of percolation will result in large losses. Conditions are also favorable for large losses by evaporation and transpiration so that a large use of water cannot be avoided.

Rice in the southern states is grown in Louisiana, Texas, and Arkansas. Irrigation practice varies. Water is usually first applied when the rice plants are about 6 in. high. Irrigation is not usually required at the time of seeding. Flooding is continued through the growing season unless the fields are drained for 2 to 3 weeks after about 3 weeks of submergence for the control of rice weevil. About 20- to 30-in. depth of irrigation in addition to the 12 to 20 in. of rain are needed for good yields.[15] The higher humidity in these areas results in a smaller total water requirement than that needed in California rice areas.

Rice has been grown in California since 1912. Early practice consisted of two to four flushing irrigations during the month after seeding, followed by continuous submergence until the fields were drained for harvest. Much present practice consists of

continuous submergence from the time of seeding. It has been found that the rice will sprout under submergence and that water grass and some other weeds can be more effectively controlled with early submergence than with the former practice. Continuous submergence is general on old rice lands where trouble with water grass occurs and permits using the land for rice for longer continuous periods.[16] For continuous submergence from the time of seeding, the depth of water is kept at 4 to 8 in.; for submergence a month after seeding the depth is gradually increased to a similar amount. There is practically no rainfall during the growing period in California rice areas and the entire moisture supply comes from irrigation. For clay and adobe soils 5 acre-feet per acre is sufficient with good practice, much actual practice uses 6 to 8 acre-feet per acre where the soil is more pervious or where leakage through the levees or other wastes occur. Rice should not be grown on soils through which larger amounts of percolation occur.

ROOT CROPS

The two principal root crops grown under irrigation are potatoes and sugar beets. As the commercial yield of both of these crops is represented by the root growth, the plants above ground serving only as an aid to root development, the irrigation practice is directed toward the production of the largest yield of roots. The quality of the crop is also an important item in the value of the yield and is subject to more variation than with forage or cereal crops.

Both potatoes and sugar beets develop their main vegetative growth before the production of the commercial portion of their yield. Adequate moisture is needed during the earlier growth to insure thrifty plants but the yield is affected to a less extent by shortages in moisture during this period than during the period of main root enlargement. Checking of growth during the later periods results in ripening with new growth following irrigation which affect the uniformity and shape of potatoes and the quality of sugar beets.

Potatoes.—Potatoes are grown under a wide variety of conditions in the western states with a consequent variation in their irrigation practice. Many potatoes are grown without irrigation; in other areas only supplemental irrigation may be required;

while in some localities all moisture must be secured from irrigation.

Where the moisture is deficient at the time of seeding, irrigation should be applied before planting rather than after. The moisture from rainfall or irrigation at the time of seeding should be sufficient to carry the plants through their earlier growth. In many areas no irrigation until the blossom period will be required. While early irrigations should be applied if actually needed, some early restriction in moisture will not reduce yields. An irrigation at blossoming time when the tubers are forming is usually followed by light applications at 1- to 2-week intervals until the crop is ready to mature. As potatoes are not deep-rooted, it is

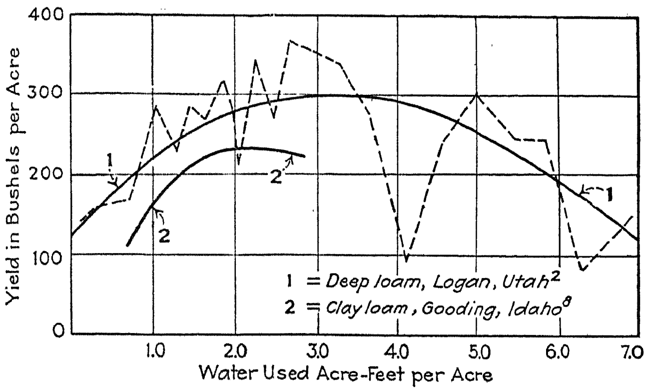


FIG. 32.—Results of experiments on the amount of water used and the resulting yield for potatoes. (*Adapted from Harris,*[2] *Welch.*[8])

only necessary to moisten a depth of soil of 2 to 4 ft. and frequent light irrigations are preferable to fewer heavier applications. A period of 30 to 50 days should be allowed after the last irrigation for ripening of the crop.

Potatoes are planted in rows varying from 33 to 48 in. apart. Furrows are formed by the cultivation and are gradually deepened as the plants become larger. Deep furrowing is desirable so that the water will penetrate to the feeding roots below the tubers. Saturation of the soil around the potatoes may cause diseases or prevent even growth in heavy soils after drying. In some areas, irrigation in alternate furrows is practiced. This is advisable, if at all, only in soils of good lateral moisture movement where the closer row spacings are used.

Figure 32 shows the results of experiments on the effect of the amount of water used on the yield. Curve 1 represents the results of 216 tests at Logan, Utah,[2] on a loam soil; the dotted line connects the points of actual record and the heavy line shows the average relationship indicated by all results. Similarly to results previously presented for other crops, the individual results show variations from the general trend. The number of observations are sufficient, however, to indicate the general effect of amounts of use larger and smaller than those giving the best results. The mean annual rainfall at Logan of 16.2 in. is not included in the use of water shown.

The results in Curve 2 were obtained at Gooding, Idaho,[3] on a medium-heavy soil during 4 years' observations. The average annual precipitation for these years was 9.73 in. Two, four, and six irrigations of about 5-in. depth each were used. Two irrigations were insufficient to produce a good yield. Four irrigations gave as good yield as six applications.

The total amount of water per season required for good yields with potatoes on medium soils varies from 6-in. depth, where only supplemental irrigation is needed, to 1½- to 2-ft. depth, where the full moisture supply is secured from irrigation. For similar climatic and soil conditions, potatoes usually require somewhat more water than cereals and from one-half to two-thirds of the amount required for alfalfa. Water is required later in the season for potatoes than for cereals. Potatoes should not be planted unless such later-season water will be available. For full irrigation, three to five applications are typical. On coarser soils, depths of irrigation used may be as large as 3 ft.

Sugar Beets.—Sugar beets are grown under a wide range of climatic conditions in the western states. In some coastal areas of southern California either irrigation is not used or only one application may be needed. In other areas entire dependence for moisture may be placed on irrigation.

The spacing of rows varies from 18 to 24 in., irrigation being applied in furrows between the rows. The relatively narrow row spacing limits the depth of furrows that can be used without covering the plants so that cross flooding between furrows frequently occurs. This is not directly harmful to the plants if water does not stand on the fields.

It is thought by many that early irrigation tends to shallow rooting and short rounded beets of smaller tonnage. Experi-

mental results do not confirm this view. With retentive soils having adequate moisture at planting, early irrigations are not usually needed but should be applied whenever the crop shows need for water. During the latter portion of the growing period when the main growth of the beets occurs, a deficiency in soil moisture causes a checking in the rate of growth which will not be recovered by later irrigations.

Sugar beets may utilize moisture to a depth of 6 ft. Somewhat heavier individual irrigations can be used effectively than for potatoes. Irrigation in alternate furrows is practiced in some areas, the first irrigation being applied in one set of furrows and the succeeding one in the remainder. A third irrigation, if needed, is more usually applied in all furrows. Such alternate-furrow irrigation avoids wetting the whole area and reduces soil evaporation. Yields may be reduced, however, in soils where the lateral movement of moisture is insufficient to meet across the wider spacing.

The water requirements of sugar beets are similar to those for potatoes. The ripening period after the last irrigation is not so long as for potatoes and a later irrigation may be needed for beets. On medium soils the total amount applied varies from less than 1 acre-foot per acre for supplemental use to 1½ to 2 acre-feet per acre for full irrigation. Experiments on the effect of variations in the yield with different depths of irrigation show similar results to those secured with potatoes, the yield increasing with the depth applied within the limits of usual practice and decreasing with excess use. The rates of decrease with excess use for sugar beets are usually less marked than those for potatoes, as the beets are less sensitive to excess moisture. The number of irrigations used varies from one to three or four, except on coarse soils where additional applications may be needed. For such coarse soils the total use may be as large as 2½ to 3½ acre-feet per acre.

ORCHARDS

Orchards include all tree crops such as deciduous and citrus fruits, vines, and nuts. Each of these groups includes several individual types. The more important irrigated deciduous fruits are the apple, peach, prune, plum, pear, apricot, and cherry. The citrus fruits include the orange, lemon, grapefruit, and avocado. Vineyards include the wine, raisin, and table

varieties. English walnuts and almonds are the more important nuts.

The wide variety of the products and the climatic conditions under which they are grown result in widely varying irrigation practices. Orchards are perennials whose commercial yield in any year is affected by the practices followed during preceding years as well as during the current season. Quality of product is a more important element in the value of the crop than for other types. Injuries from disease which may in turn be affected by the irrigation practice are a larger factor than for annual crops. All of these conditions make it much more difficult to correlate the irrigation practice with its effect on the yield and there is much less experimental work of this character available for orchards than for other irrigated crops. Present practice in orchard irrigation is more largely the result of general experience and observation than of controlled experiments.

While the character and depth of roots of different types of orchards vary, the depth is usually sufficient to enable fairly heavy applications to be retained within reach of the trees. With orchards it is not advisable to delay irrigation until the shortage of moisture affects the tree. Such delay may result in injury to the yield before water can be applied and the tree recover. The need of irrigation of orchards is judged by general experience or by examining the moisture condition of the soil. Such examinations may be general, such as with the shovel to secure soil just below the drier surface, or definite, such as by actual soil borings to 4 to 6 ft. depth with oven drying of the samples obtained. This latter practice is coming into increasing use in some citrus areas where water is expensive and difficult to obtain and where the value of the crop supports the cost of such observations.

Deciduous Orchards.—The most extensively irrigated deciduous fruit is the apple. Apples can be grown under a wider range of climatic conditions than other fruits. Other irrigated deciduous orchards are largely limited to the Pacific Coast states or inland localities having less severe climatic conditions than occur in much of the area of the western states.

Many areas producing deciduous fruits, particularly in the coast states, were planted under the expectation that irrigation would not be required. This applies to many California areas receiving 15 to 20 in. of mean annual rainfall occurring mainly

during the winter months, as well as more northern coastal valleys receiving larger rainfall. Good results were frequently secured in the early growth and bearing of the trees, but it has been found in many of these areas that the maintenance of good yields of high-quality fruit with mature orchards requires supplemental irrigation. In nearly all of such areas where water can be secured at a feasible cost, irrigation is now generally practiced. The use of winter rainfall is limited by the moisture-storage capacity of the soil and even on deep retentive soils sufficient moisture cannot be retained from winter rains to meet the moisture needs of heavy production during the summer growing period.

There has been much discussion regarding the effect of irrigation on the flavor and keeping quality of the fruit. While over-irrigation may result in fruit of poor flavor, with proper practice there is little difference between the irrigated and unirrigated products. In areas where fairly good production may be secured without irrigation, irrigation has been found to improve the uniformity and color and to reduce windfalls.

Many consider that irrigation shortly before ripening reduces the keeping quality and may cause splitting. Where the moisture conditions have been continuously favorable, with a resulting continued steady growth of the crop, late irrigations before ripening have not been found to be detrimental. Where the soil has become dry and the fruit has begun to mature, some splitting may follow an irrigation. The general rule applicable to all deciduous trees is to maintain an adequate moisture supply continuously available to the tree so that growth is never seriously checked. Fluctuations of moisture within this standard do not produce harmful effects and avoid the disadvantages that may follow too wide moisture variations.

Intercrops or cover crops are frequently used in orchards. Intercropping is more usual in young orchards where the tree roots do not utilize the full soil area. The water requirements with intercropping equal the sum of those for the trees and the intercrop if the trees are to be fully supplied. Cover crops are used for green manuring. In California, cover crops can be grown during the winter months and their moisture needs supplied from rainfall. Such use of rainfall, however, decreases the soil moisture that might be stored for use by the trees during the summer season and increases the irrigation requirement by

the amount of soil-moisture storage used by the cover crops. Earlier plowing under the cover crop reduces its effect on the moisture supply of the trees. Permanent cover crops are grown in some areas where winter temperatures prevent winter crops. Alfalfa is frequently used for this purpose. The water requirement under such practice is increased over that needed for clean culture.

The details of practice with different deciduous orchards in different areas vary so widely that an inventory of the methods used would be of limited general application. The following illustrations are typical of these variations.

Several deciduous fruits mature their crop sufficiently early in the season so that irrigation after picking is required to maintain the tree in a thrifty condition during the remainder of the growing season while the buds for the succeeding season are forming. In areas where winter injury does not occur, it is usual to attempt to hold the leaves as late as practicable in order to get full bud growth. A late-season water supply is essential for such practice. It is usual to irrigate deciduous fruits after harvest in the fruit areas of California of lower altitude. This also permits starting cover crops before the winter rains begin.

The apple tree makes its main wood growth in the first half of the growing season and the main volume of its crop growth in the second half. Irrigation in the first half of the season should be directed toward maintaining a thrifty condition of the tree without over-stimulation of limb growth. Later irrigations should be applied so that there is a continuously favorable soil-moisture content until the maturity of the fruit is assured. As apples are grown in many areas having low winter temperatures, care is used to check late-season growth in time for the tree to become dormant before freezing occurs. A winter irrigation after the tree has become fully dormant is practiced in some areas if the winter rainfall is deficient. Injury from very low temperatures or drying winds is less if the soil is moist.

With peaches the early-season growth of the fruit is slow until the fruit pit hardens. It is essential that adequate moisture be available at this time. Irrigations are usually needed until harvest at 3- to 4-week intervals on sandy land and every 4 to 6 weeks on medium to heavy soils. For prunes, much California practice applies three irrigations, in early summer, midsummer, and after harvest. Sandy or shallow soils require more frequent

and lighter applications. Mature trees will use the available moisture in retentive soils to depths of 5 to 6 ft. in 4 to 6 weeks.

The total moisture needs of a mature deciduous orchard are about 2 acre-feet per acre per season. The irrigation requirement represents the portion of this need which is not supplied from rainfall. Ground water within 10 or 12 ft. of the surface will also supply some moisture for use by the trees and reduce the amount of surface irrigation needed. Where soil conditions permit efficient application, the total irrigation requirement should not exceed 2 acre-feet per acre without aid from other sources of moisture; on some coarse soils larger applications may be needed. For much deciduous-orchard practice the total depth of irrigation used is from 1 to 1½ acre-feet per acre. For retentive soils the number of irrigations varies from two to four with a tendency toward a larger number of applications for apples than for other fruits.

Citrus Orchards.—Citrus trees are evergreen and require moisture throughout the year. The long growing season with high temperatures results in a larger water requirement than that for deciduous orchards.

The total annual water requirement of mature citrus orchards in Southern California[17] is about 30 to 40 acre-inches per acre. As a portion of the total requirement is secured from rainfall, the irrigation requirement is about 12 to 15 acre-inches per acre in the more humid coastal areas, about 18 acre-inches per acre in the intermediate areas, and 24 to 28 acre-inches per acre in the interior valleys. The requirement for young orchards may not exceed one-half to two-thirds that needed for mature groves in full bearing. In the Imperial Valley and in Arizona where the rainfall is too small to be useful to the trees, grapefruit has a larger requirement; 24 to 30 acre-inches per acre per season may be used on young trees and 36 to 42 acre-inches per acre on older orchards in bearing.

Citrus trees are more shallow-rooted than most types of deciduous trees so that lighter individual irrigations are usual. Typical practice would be represented by irrigations of 3 to 4 in. in depth at intervals of 3 to 6 weeks from April to October. In seasons of deficient winter rainfall additional irrigations may be required. Economic conditions in citrus culture permit more care in applying water and the water used is more uniformly distributed and

more completely secured by the trees than is usual with similar depths of irrigation for other crops.

Nuts.—Irrigated nuts are grown in California and to a limited extent in some other states. While there is some planting of several kinds, commercial production consists mainly of walnuts and almonds.

Walnuts are planted on a wider spacing than other orchards. Their water requirement per acre is not reduced by such planting, however. An adequate moisture supply is essential from the time the shells begin to harden until the latter part of the summer. In some Southern California areas, an irrigation after the removal of the crop is advisable to prevent winter drying out with die-back of new wood growth. Late irrigation should be avoided on young trees. The seasonal depth of irrigation needed varies from 12 to 18 in. in Southern California coastal areas of larger rainfall and higher humidity to 24 in. in arid areas of higher temperature. The depths used in the northwest are usually from 9 to 18 in. Walnuts are also grown in some areas where irrigation is not practiced.

Almonds have a smaller water requirement than many other trees. If the soil is dry, an irrigation just before the hull begins to split will reduce stick tights. A light irrigation after harvest aids bud formation for the following year.

Grapes.—Irrigation practice for grapes is more variable than for many other crops. Many vineyards are not irrigated in semi-arid areas. Much California practice consists in irrigating in the spring, at blossom time, and when grapes are of small shot size. Later irrigations may be applied on soils of small moisture holding capacity. Irrigations near the time of ripening have been considered to result in poorer keeping qualities but experience indicates that no harmful effects occur unless the soil has become too dry prior to the irrigation.

TRUCK CROPS

Truck crops include the vegetables, melons, bush fruits, and berries. Both the varieties of the crops included and the conditions and purposes of their production vary so widely that their irrigation practice is less uniform than for other classes of crops.

Truck crops are generally shallow-rooted. Consequently only light irrigations are needed to meet the moisture requirements of the depth of soil from which they secure their supply. Many of

these crops are sensitive to shortages of moisture, particularly at the ripening period, and frequent light irrigations are usual. As irrigation in furrows is practiced, such light applications can be readily accomplished. A heavier irrigation is frequently applied before seeding for the annual truck crops. Less frequent irrigations are usual during the earlier part of the growing season with such crops as tomatoes, in order not to overstimulate vine growth.

The total water requirement for truck crops is generally from 1 to 1½ acre-feet per acre, where single annual crops are grown, to 1½ to 2½ acre-feet per acre for perennials or double-cropping annuals. Dependability of the supply during critical periods of growth is as important as the total amount available.

COTTON

Cotton is grown under irrigation in California, Arizona, New Mexico, and western Texas. Irrigated cotton represents only a small part of the total production in the United States of this crop.

An irrigation before planting is usual if adequate moisture is not available from rainfall. This irrigation, if applied, should be thorough. Following seeding, overirrigation should be avoided, as excess moisture stimulates vegetative growth and delays fruiting. After the squares have formed, continuously favorable moisture conditions should be maintained by light irrigations. These may be needed at 10- to 14-day intervals on light soils. Drying of the soil during the latter stages of growth may cause shedding and loss of yield.

Owing to its long growing season the water requirement of cotton is larger than that for most annual crops. The depths of water used vary with the climatic conditions from 8 to 20 in. in the Upper Rio Grande Valley to 2 to 4 ft. in Salt River and Imperial Valleys.[18] Where properly applied, good yields are secured from the smaller amounts of use.

References

1. Snelson, W. H.: Irrigation Practice and Water Requirements for Crops in Alberta, *Bull.* 7, Irrigation Series, Dept. Int. Canada, 1930.
2. Harris, F. S.: The Duty of Water in Cache Valley, Utah, *Utah Agr. Exp. Sta. Bull.* 173, 1920.
3. Thompson, C. A., and E. L. Barrows: Soil Moisture Movement in Relation to Growth of Alfalfa, *New Mexico Agr. Exp. Sta. Bull.* 123, 1920.

4. WELCH, J. S.: Experiments with Legume Crops under Irriga *Idaho Agr. Exp. Sta. Bull.* 94, 1917.
5. BECKETT, S. H., and M. R. HUBERTY: Irrigation Investigations Field Crops at Davis and at Delhi, Calif., 1909–1925, *California Exp. Sta. Bull.* 450, 1928.
6. MARR, JAMES C.: The Use and Duty of Water in the Salt River Va *Arizona Agr. Exp. Sta. Bull.* 120, 1927.
7. PITTMAN, D. W., and G. STEWART: Twenty-eight Years of Irriga Experiments near Logan, Utah, 1902–1929, *Utah Agr. Exp. Sta.* . 219, 1930.
8. WELCH, J. S.: Irrigation Practice, *Idaho Agr. Exp. Sta. Bull.* 78, 19
9. *Washington Agr. Exp. Sta. Rep., Bull.* 229, June 30, 1928.
10. BECKETT, S. H., and R. D. ROBERTSON: The Economical Irrigatio Alfalfa in Sacramento Valley, *California Agr. Exp. Sta. Bull.* 1917.
11. DEAN, H. K.: The Management of Sandy Soils under Irrigat *Oregon Agr. Exp. Sta. Bull.* 177, 1921.
12. WELCH, J. S.: Experiments with Small Grains under Irrigation, *Id Agr. Exp. Sta. Bull.* 93, 1917.
13. SINGLETON, H. P.: The Production of Cereals under Irrigation in Wa ington, *Washington Agr. Exp. Sta. Bull.* 240, 1930.
14. PITTMAN, D. W.: Maintaining the Productivity of Irrigated La *Utah Agr. Exp. Sta. Bull.* 188, 1924.
15. CHAMBLISS, C. E.: Prairie Rice Culture in the United States, *U. Dept. Agr. Farmers Bull.* 1092, 1920.
16. JONES, J. W.: How to Grow Rice in the Sacramento Valley, *U. S. D of Agr. Farmers Bull.* 1240, 1931.
17. VAILE, R. S. A Survey of Orchard Practices in the Citrus Industry Southern California, *California Agr. Exp. Sta. Bull.* 374, 1920.
18. MARR, J. C., and R. G. HEMPHILL: The Irrigation of Cotton, *U. S. D of Agr. Tech. Bull.* 72, 1928.

CHAPTER V

GENERAL WATER REQUIREMENTS

In addition to the factors affecting the net water requirements of the various crops as discussed in Chap. IV, the planning of the water supply for an irrigation project requires consideration of the factors affecting the gross water requirements and the distribution of the demand during the irrigation season. Such matters are the concern of both the canal management and the landowner, as they are both directly affected by any inadequacies in the supply that require adjustments in crop practice. Such adjustments may be either in the total amount of use if the total supply is insufficient or in time of use if the run-off does not coincide in time with the period of demand and storage is not available.

The projects of the U. S. Bureau of Reclamation are distributed throughout the western states and include all varieties of conditions of soils, climate, and crops. As their records of operation are more complete and are more readily available than those for projects of other forms of organization, the results of their use have been used to illustrate the variations in the general water requirements of irrigation systems. In general, the projects of the Bureau have adequate water supplies so that the choice of crops and the irrigation practice are not limited by shortages in the available water supply.

GROSS USE OF WATER

The gross amounts of diversion by canal systems vary with all of the factors that affect the conveyance and use of water. Records of different canal systems show differences of several hundred per cent, resulting from differences in character of construction, soil, crop, climatic, and water-supply conditions. For such an extent of variation, average use has only limited usefulness as a guide to the probable use under any canal system. While no complete records are available, average diversion by the larger canal systems is probably about 5 acre-feet per acre irrigated per year. For short growing seasons, more favorable rainfall, or retentive soils, gross use may not exceed 2 acre-feet per

acre irrigated. For long canals or coarser soils causing larger conveyance losses or for conditions resulting in larger deliveries to the land, gross diversion may equal or exceed 6 to 8 acre-feet per acre irrigated.

The irrigable area under any canal system is never all irrigated in any season. In addition to the entire farms which for various reasons may not be operated in some years, the entire area of each farm cannot be devoted to crops even on fully developed farms. Roads, canal rights of way, rough land, and building sites all reduce the cropped and irrigated areas. On large systems, several years are required for settlement and less than one-half of the area may be irrigated after 5 years of operation. Records of gross use should specify the basis used in determining the area irrigated. Unless otherwise specified, the use in the following tables is based on the area actually cropped and irrigated.

TABLE XIV.—AVERAGE GROSS DIVERSION OF TYPICAL PROJECTS OF U. S. BUREAU OF RECLAMATION[1]

Project	State	Area irrigated, acres	Miles of canals and laterals operated	Mean annual precipitation, feet	Gross diversion, acre-feet per acre irrigated per season	General character of soil
Belle Fourche	S. D.	45,200	547	1.34	2.35	Heavy
Klamath	Calif. and Ore.	43,300	240	0.86	2.75	Medium
Lower Yellowstone	Mont. and N. D.	17,500	202	1.04	3.82	Heavy
Huntley	Mont.	19,400	232	1.00	4.08	Heavy
Shoshone-Garland Unit	Wyo.	32,400	279	0.42	4.33	Medium
Minidoka South Side	Idaho	44,900	275	0.85	4.38	Medium
North Platte	Nebr.	107,700	1,154	1.28	4.55	Medium
Yakima Sunnyside	Wash.	91,700	602	0.48	4.70	Medium
Orland	Calif.	14,600	135	1.29	4.95	Light
Carlsbad	N. M.	22,500	45	0.92	5.12	Medium
Boise	Idaho	145,600	1,004	0.81	5.14	Light
Newlands-Carson Division	Nev.	38,800	319	0.40	6.40	Medium
Uncompahgre	Colo.	61,200	470	0.81	7.49	Medium
Rio Grande	N. M. and Tex.	96,800	485	0.66	9.95	Medium
Umatilla	Ore.	11,000	173	0.75	10.04	Light
Yuma	Calif. and Ariz.	52,000	336	0.66	10.75	Medium

Table XIV contains the results of the records of gross use of water on a selected group of projects of the U. S. Bureau of

Reclamation.[1] These projects have been arranged in the order of the amount of their average gross use per acre. The systems having the smaller gross use per acre are generally those of shorter growing season or larger and more favorably distributed rainfall where the soils are medium to heavy in texture. Intermediate amounts of gross use are shown on systems of medium soils with fairly favorable conditions regarding conveyance loss and waste. For such projects a gross use of 4.5 to 5 acre-feet per acre irrigated is typical. Systems having relatively large gross use are ones for which some unfavorable factor, such as coarse soils, long season, or excessive waste in operation, affects the results. On the Rio Grande Project, excess water is diverted by the upper canals and returned to the river for rediversion in lower canals. The gross use reported includes such reuse. On the Yuma Project excess water is diverted for power use and silt control, the excess diversion being returned to the river. Use on the Umatilla Project includes both large conveyance loss and use on the lands due to the sandy soils served by this project. The results shown in Table XIV illustrate the importance of local factors in the amount of use and the necessity of considering local conditions in determining proper use.

Table XV.—Gross Use on Sunnyside Project, Washington

Year	Water Diverted, Acre-feet per Acre Irrigated
1898	11.4
1899	10.6
1900	10.2
1901	9.6
1902	9.1
1904	6.0
1906	6.5
1909	5.5
1912	5.4
1914	4.9
1917	4.7
1920	4.4
1923	4.6
1927	4.7
1928	5.0
1929	5.2
1930	5.6

Effect of Age of Canal on Use.—The gross use per acre generally diminishes with an increase in the time a system has been

operated. In the first years of operation of new systems the area irrigated is usually scattered and small and the water supply is in excess of the needs. More liberal conditions of service can be permitted in the earlier years. The canals may need to be operated at as high stage for delivery and for as much mileage as for full development, so that conveyance losses are high. Use generally becomes stabilized after 10 to 15 years of operation and, while variations occur from year to year with the climatic differences and shifts in crops, further permanent changes occur slowly. Use may increase with changes to crops of larger need, such as from grain to forage or where drainage may result in more surface irrigation. The more usual tendency is toward a decrease, as diversity of crops more often reduces the average use and improvements in canals reduce conveyance losses.

The variations in gross diversion with the continued use of the canal system are illustrated by the records of the Sunnyside Canal in Washington. The results as compiled from the records of the U. S. Bureau of Reclamation are shown in Table XV.

NET WATER REQUIREMENTS

Records of the net use or delivery to farms for typical projects of the U. S. Bureau of Reclamation[1] similar to those for gross use in Table XIV are given in Table XVI.

Table XVI gives the general factors affecting the use of water except the length of the growing season. For heavier soils and shorter seasons, use may be as low as 1.50 acre-feet per acre. Average conditions result in a use of from 2.25 to 3.0 acre-feet per acre. With porous soils or other unfavorable conditions, use may average 4 to 5 acre-feet per acre. These rates of use exceed the transpiration and evaporation and cause additions to the ground water which usually result in waterlogging much of the land served unless drainage is provided. These illustrations of net requirement, like those for gross use, emphasize the variations that result from local conditions and the necessity of considering such conditions in forecasting the water requirements of irrigation systems. Details regarding use for different crop and soil conditions have been discussed in Chap. IV.

RELATION BETWEEN GROSS AND NET USE

The proportion of the total diversions which are represented by the canal seepage, the regulation waste, and the delivery to the

TABLE XVI.—AVERAGE DELIVERIES TO FARMS OF TYPICAL PROJECTS OF U. S. BUREAU OF RECLAMATION[1]

Project	Precipitation in growing season, feet	Mean temperature in growing season, degrees Fahrenheit	Percentage of area in different crops: Alfalfa, hay, and pasture	Small grain	Furrow crops	Trees	Water delivered to farms, acre-feet per acre	General character of soil
Belle Fourche....	0.86	65	62	22	16	..	1.22	Clay and sandy loam
Klamath.........	0.18	60	77	21	2	..	1.43	Sandy loam
Lower Yellowstone	0.71	64	45	33	22	..	1.34	Deep sandy loam
Huntley.........	0.63	64	42	34	24	..	1.39	Heavy clay to light sandy loam
Shoshone-Garland	0.33	59	59	28	13	..	2.38	Light sandy to heavy clay
Minidoka South Side...........	0.53	59	50	28	22	..	2.54	Sandy loam
North Platte.....	0.81	66	36	26	38	..	2.23	Sandy loam mainly
Yakima-Sunnyside...........	0.21	63	57	7	21	15	3.29	Mainly sandy loam
Orland..........	0.37	70	53	5	19	23	3.17	Sandy and gravelly loam, silt loam, clay loam
Carlsbad.........	0.86	66	33	4	63	..	2.36	Sandy loam
Boise............	0.38	62	53	31	13	3	3.60	Clay loam, light sandy loam, and sandy loam
Newlands-Carson Division.......	0.25	59	85	11	4	..	2.88	Mixed
Uncompahgre....	0.55	61	47	25	25	3	5.76	Sandy gravel, adobe and clay loam
Rio Grande......	0.60	66	37	8	53	2	2.89	Alluvial sandy loam
Umatilla.........	0.35	60	85	1	6	8	5.02	Sandy and sandy loam
Yuma...........	0.33	72	39	3	58	..	3.01	Alluvial, bottom lands

farms for the systems of the U. S. Bureau of Reclamation listed in Tables XIV and XVI is shown in Table XVII. The amount of canal seepage depends on the average distance water is conveyed and the texture of the soil in which the canals are constructed. Regulation waste represents the water diverted into the system and allowed to escape from the canals and at the lower ends of the laterals.

TABLE XVII.—CONVEYANCE LOSS, REGULATION WASTE, AND DELIVERIES TO FARMS FOR TYPICAL PROJECTS OF U. S. BUREAU OF RECLAMATION[1]

Project	Percentage of total diversions			Remarks
	Canal and lateral losses	Regulation waste	Delivery to farms	
Belle Fourche	33	15	52	
Klamath	39	9	52	
Lower Yellowstone	44	21	35	
Huntley	36	30	34	
Shoshone-Garland	38	7	55	
Minidoka South Side	39	3	58	
North Platte	43	8	49	
Yakima-Sunnyside	23	7	70	
Orland	27	9	64	Two-thirds of canal mileage, concrete lined
Carlsbad	48	6	46	
Boise	28	2	70	
Newlands-Carson Division	41	14	45	
Uncompahgre	13	10	77	
Rio Grande	32	39	29	
Umatilla	32	18	50	82 per cent of canal mileage lined or pipe
Yuma	14	58	28	

With favorable soils, conveyance losses may be less than 20 per cent of the diversion. Similarly small losses may occur where the water used contains much silt as illustrated by the Yuma Project. More usual values for conveyance losses are 25 to 40 per cent. Long diversion or main canals or coarse soils may result in losses exceeding 40 per cent. All of the projects have complete distribution systems from the point of diversion to each farm.

Smaller systems with short diversion canals would have less loss for similar soils.

Of the canal systems listed in Table XVII, only two, the Orland and Umatilla, have any large proportion of concrete-lined canal. On some California systems consisting of concrete-lined canals and concrete pipe, conveyance losses are as small as 5 per cent of the diversion.

Regulation waste may be a large item where excess water is available, as it is a convenience in operation to carry some surplus flow. This permits flexibility in operation and delivery on shorter demands. Where excess water is not available, waste may be held to a small percentage of the diversions. The large waste on the Rio Grande Project is due to diversion in excess of needs and return to the river for the lower units of the project; that in the Yuma Project to excess diversions for power and silt control.

SEASONAL USE OF WATER

The seasonal distribution of the demand for water varies with climatic conditions and crops. As the crops are also largely governed by the climatic conditions, the climate is the main factor in determining the seasonal use on large systems having diversity of crops. The seasonal use is also affected by the adequacy and availability of the water supply and by the soil. While the seasonal demand is generally similar under the different canals in any locality, water-supply estimates for any project should be based on a consideration of all factors affecting its individual use.

Plant growth starts slowly in the spring when temperatures begin to exceed the minimum limit for different crops. Some growth of forage crops begins when the temperature during the day reaches 40° F. Such growth is very slow until the daily mean temperature increases and the daily minimum is above 32°. Moisture use in the early season is similarly slow and irrigation is not required until temperatures have increased and normal growth has begun. Too early irrigation may retard growth by reducing soil temperatures. Such irrigations tend to result in the growth of the hardier weeds and grasses at the expense of the alfalfa or planted forage crops. The annual crops more sensitive to low temperatures are not planted in the early season. There

may be a demand for early irrigation for such lands where irrigation before planting is needed.

The first demand for water under a canal system is for the coarser-textured soils. Such soils have a smaller moisture holding capacity and also become warmer more quickly. This results in earlier growth and use of the available moisture.

The demand for water at the end of the irrigation season diminishes gradually as different annual crops mature or growth is completed on perennial crops. While the beginning and ending of the operation season will vary somewhat in different years, owing to the character of the individual seasons, the amount of such variation is usually small in arid areas. In semi-arid areas differences in the amount and time of occurrence of rainfall cause more variation in the irrigation season in different years.

Effect of Kind of Crop.—An illustration of the effect of the kind of crop on the seasonal demand is presented by results in southern Idaho,[2] from which Table XVIII has been compiled.

TABLE XVIII.—AVERAGE USE BY MONTHS ON SELECTED FIELDS OF MEDIUM CLAY AND SANDY LOAM SOILS IN SOUTHERN IDAHO[2]

Dates	Average use on 119 fields of grain		Average use on 52 fields of alfalfa and clover		Average use for equal areas of the two types of crop	
	Acre-feet per acre	Percentage of total	Acre-feet per acre	Percentage of total	Acre-feet per acre	Percentage of total
Apr. 1 to 15	....	.....	0.02	0.8	0.01	0.5
Apr. 16 to 30	0.01	0.7	0.02	0.8	0.02	1.0
May	0.14	9.3	0.60	24.1	0.37	18.5
June	0.68	45.9	0.44	17.7	0.56	28.0
July	0.57	38.1	0.73	29.3	0.65	32.5
Aug	0.09	6.0	0.58	23.3	0.34	17.0
Sept	....	.....	0.10	4.0	0.05	2.5
Total	1.49	100.0	2.49	100.0	2.00	100.0

A canal serving grain alone would need to have nearly as large a capacity as one serving all forage crops owing to the peak demand in June, although the total amount of water used for the season

would be only 60 per cent of that used for alfalfa. Where the two types of crops are combined, the peak demand would be 11 per cent less than that for an area serving forage crops only.

The variation in time of demand for different crops under conditions in Utah[3] is shown by Fig. 33. Cereals require water mainly in the earlier summer months; sugar beets, potatoes, and corn require little water before July but need water through August. Alfalfa has a steady demand throughout the irrigation season. As the water supply for irrigation is mainly derived from the natural flow of streams draining the higher mountainous areas which have a relatively large run-off from melting snow in the earlier summer months with low flow in July and August, the growing of large areas of crops needing late-summer water requires storage. On canal systems which have only a limited late-summer flow available, it may be necessary to limit the proportion of such late-season crops and to grow early-season crops, such as cereals, on much of the land.

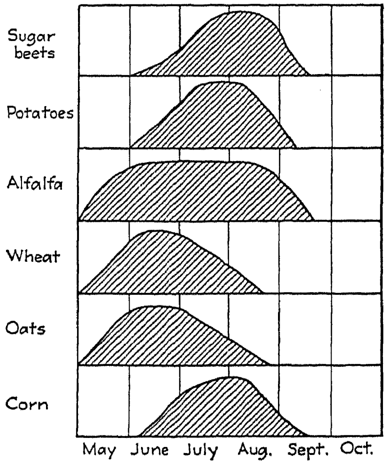


FIG. 33.—Diagram representing the seasonal use of water on various crops in Cache Valley, Utah. (*Harris.*[3])

Effect of Character of Water Supply.—Seasonal use of water may have to be adjusted to the time at which water may be available. The effect of the character of the water supply on the seasonal use is illustrated by the examples in Table XIX and Fig. 34, for typical California conditions. The monthly run-off and use are both expressed in terms of percentage of the total for the year. As the use by the canals shown is less than the total run-off of the streams from which they divert, the percentage of annual use in some months may exceed the percentage of the annual run-off for the same months.

Fresno River has a drainage area of relatively low elevation. The precipitation occurs during the winter months, mainly in the form of rain. Run-off diminishes rapidly after the end of the rainy season. Use by the Madera Canal and Irrigation Co. is

adjusted to the time of run-off with a larger early-season diversion than that under the Turlock Irrigation District which has a similar growing season. Diversions from Fresno River are dependent on the direct flow, as storage has not been constructed. Many users under this canal secure additional water by pumping from wells; such well water is not included in the use shown.

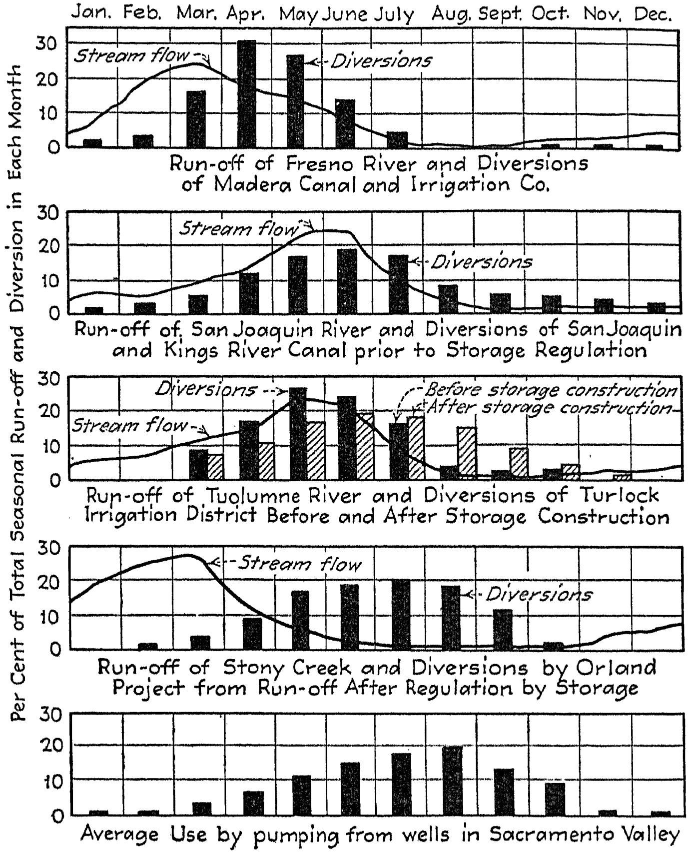


FIG. 34.—Effect of the character of water supply on the seasonal use for irrigation for typical California conditions.

The San Joaquin River has a large drainage area of high elevation on which the precipitation occurs largely as snow. Melting occurs so as to result in large run-off in the early summer months. Use by the San Joaquin and Kings River Canal, which has an early right on this stream, occurs largely during the main summer

months of direct crop demand. Some diversion, mainly for pasturage, is made throughout the year. The use by this system is well adjusted to the character of water supply. In recent years storage for power use has increased the low-water stream flow.

TABLE XIX.—EFFECT OF THE CHARACTER OF WATER SUPPLY ON THE SEASONAL USE FOR IRRIGATION FOR TYPICAL CALIFORNIA CONDITIONS

Stream and canal system	Percentage of mean annual run-off and diversion for irrigation occurring in each month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Fresno River....	7.1	18.4	24.4	17.4	14.2	7.9	2.3	0.5	0.3	1.6	2.1	3.8
Madera Canal and Irrigation Co...........	2	3.5	16	31	27	14	4	0.5	0.5	0.5	0.5	0.5
San Joaquin River.........	5.5	5.0	9.0	13.3	23.4	24.2	10	3.2	1.5	1.3	1.5	2.1
San Joaquin and Kings River Canal........	2	3	5	12	17	18	17	8	6	5	4	3
Tuolumne River	6.2	6.8	11.2	15.0	23.0	21.9	8.1	1.6	0.6	1.2	1.9	2.5
Turlock Irrigation District:												
Before storage construction.	0	0	8	17	27	24	17	3	2	2		
After storage construction.	0	0	7	10	17	19	18	15	9	4	1	0
Stony Creek....	18.5	23.6	27.0	11.9	5.8	2.4	0.7	0.5	0.2	0.7	3.4	5.3
Orland Project..	....	1	3	9	17	18	20	18	12	2		
Average use by small plants pumping from wells in the Sacramento Valley........	1	1	3	7	11	15	18	20	13	9	1	1

The Tuolumne River is also a snow-fed stream. For the earlier years of its operation, the Turlock Irrigation District adjusted its use to the available natural flow supplemented by a small amount of regulating storage. Use resulted in a rise of the ground water with some sub-irrigation in parts of the district. Owing to the limitations on the late-summer water supply, storage was constructed. With late-summer water available, there is less need for large early-season use. The change in use due to storage is

well illustrated by the records of this district. Storage permits increased yields from the later cuttings of alfalfa and greater diversity of other crops.

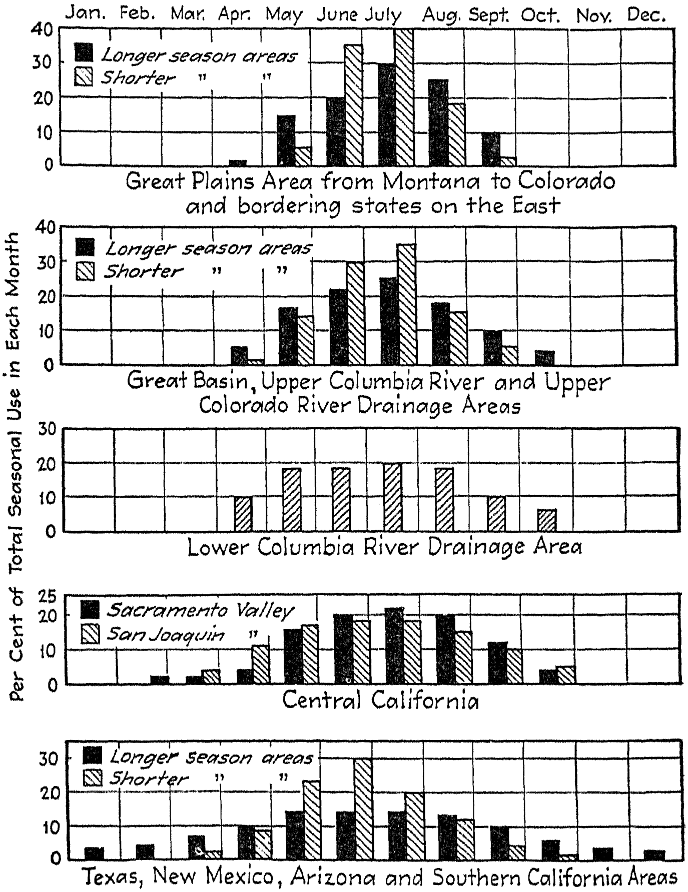


FIG. 35.—Usual distribution of use during the irrigation season for different general areas in the western United States.

The Orland Project of the U. S. Bureau of Reclamation secures its water supply from Stony Creek, a rainfall stream of the Coast Range. Storage was constructed as a part of the project. Seasonal use has little relationship to the time of run-off of this stream, as the storage regulation is sufficient to permit use in accordance with the crop demands.

Where the irrigation supply is obtained by pumping from wells on the lands irrigated, the supply is continuously available and

TABLE XX.—PERCENTAGE OF TOTAL SEASONAL DEMAND FOR DELIVERY TO FARMS DELIVERED IN EACH MONTH. TYPICAL RESULTS FOR DIFFERENT CLIMATIC CONDITIONS IN WESTERN STATES

Area	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Great Plains area, Montana to Colorado and bordering states to east:												
Shorter-season localities...	..	..	..	..	5	35	40	18	2			
Longer-season localities...	..	..	..	1	14	20	30	25	10			
Great Basin and Upper Columbia and Upper Colorado River drainage areas:												
Shorter-season localities...	..	..	..	1	14	30	35	15	5			
Longer-season localities...	..	..	..	5	17	22	25	18	10	3		
Texas, New Mexico, Arizona, and Southern California:												
Shorter-season localities...	..	..	2	8	23	30	20	12	4	1		
Longer-season localities...	3	4	7	10	14	14	14	13	10	6	3	2
Lower Columbia River Basin:												
Average conditions	..	..	..	10	18	18	20	18	10	6		
Central California:												
Average conditions, San Joaquin Valley.........	..	2	4	11	17	18	18	15	10	5		
Average conditions, Sacramento Valley......	..	..	2	4	16	20	22	20	12	4		

use can be adjusted to the crop needs. The average seasonal use for pumping plants serving a diversity of crops in the Sacramento Valley is also shown in Fig. 34. As these results are based on the amount of power used rather than direct measurements of the water pumped, the winter use shown is at least partly for other uses of power charged on the agricultural-use rate. A larger relative use in the later-summer months is shown than under canals subject to limitations in their late-season water supply.

General Seasonal Use.—Table XX and Fig. 35 show generalized seasonal use for different areas in the western states. These estimates are a composite of those presented in the various references at the end of this chapter and of other data.

The results shown in Table XX and Fig. 35 illustrate the extent of the differences that occur in the distribution of use under different climatic conditions. In the higher altitudes of the Great Plains areas the growing season is short and the rainfall meets the early-season needs. Consequently the irrigation season is confined almost wholly to the 3 months from June to August. In lower altitudes and where crops needing late summer water, such as sugar beets, are grown, the demand is more evenly distributed over a longer period.

In the more southern areas, the growing season is longer and the irrigation season may extend from 8 to 12 months. The crop demand for moisture in the San Joaquin and Sacramento Valley is similar but the larger rainfall in the Sacramento Valley reduces the early-season irrigation demand. Where irrigation continues throughout the entire year, the demand may be evenly distributed with the use in no month exceeding twice the annual average.

CONSUMPTIVE USE

Consumptive use is the quantity of water transpired by plants and evaporated from the crop-producing land. While such items of moisture supply pass into the atmosphere and return in some form at some place, they are consumed or lost from the point of view of the area to which the water has been applied. The amount of the consumptive use is dependent on the kind of crop, soil, and climatic conditions. It may also vary with the crop yield, although large yields may be obtained from fertile soils without exceeding the consumptive use for smaller yields on poor soils.

Moisture transpired or evaporated may have its origin in irrigation, rainfall, or stored soil moisture. In defining numerical values, it is necessary to specify the basis used. For local estimates it may be sufficient to know the consumptive use from irrigation alone. For comparison with other areas the soil moisture stored during the non-growing season and the rainfall during the crop season also need to be known. It is also essential to know the basis used in determining the crop area and whether the result is the gross area or the net area actually in crops.

Consumptive use may be measured in pots or tanks, on field experimental plots, for whole farms, for projects, or for general valley areas. Determinations in pots are under more close control for measurement but the results are not directly applicable to field conditions. Field experimental plots can be used where deep percolation and surface waste are prevented and account is taken of changes in soil moisture by means of soil-moisture samples. Use of larger areas give results more directly applicable to usual conditions. For such larger areas it is necessary to be able to control or measure all sources of moisture supply and escape.

For areas of single farms or fields, consumptive use will be somewhat less than the smaller values of reasonable use that have been given for different crops on medium soils in Chap. IV. For usual agricultural crops, consumptive use is largest for the forage types of crops and less for orchards and annual crops. Some types of special crops and plants have larger amounts of consumptive use; for rice with continuous submergence conditions are very favorable for large transpiration and evaporation, and consumptive use may amount to 4 to 4½ acre-feet per acre for California conditions. Observations on tules indicate a consumptive use as large as 8 to 10 acre-feet per acre. For any crop, consumptive use varies with the temperature, length of growing season, and humidity.

Records of consumptive use on large areas usually show smaller numerical values than results on plots or individual farms. The large areas include crops of small yield as well as those of average or better production. Most experiments on small areas are made on selected fields of better than average yield. The irrigated areas for projects or valleys are also determined with less complete exclusion of unused portions and may represent a larger area than that from which actual moisture loss occurs.

Records of consumptive use for large areas in the mountain states are shown in Table XXI.[10] The length of growing season between frosts is a general index of the climatic factors. The crops grown on these areas are mainly forage and cereals, with some sugar beets and potatoes in the areas of longer season. These results illustrate the extent to which consumptive use may be less than the usual rates of delivery to the land.

Records of consumptive use for areas in the San Joaquin Valley in California indicate a consumptive use, exclusive of rainfall, of about 1.7 acre-feet per acre, for areas mainly in trees and vines, to 2.0 to 2.25 acre-feet per acre, for areas containing diversified crops including a large proportion of alfalfa. For these areas the mean annual rainfall is about 9 in., occurring during the winter months. Temperature conditions permit some growth during the rainy season.

TABLE XXI.—CONSUMPTIVE USE FOR LARGE AREAS IN THE MOUNTAIN STATES[10]

Area	State	Area irrigated, acres	Mean total annual rainfall, inches	Average length of growing season between frosts, days	Consumptive use, acre-feet per acre	
					Irrigation water only	Irrigation plus crop season rainfall
Little Laramie	Wyo.	28,000	14	95	0.95	1.25
North Park	Colo.	120,000	10	60	1.0	1.2
South Platte:						
Kersey to Julesburg	Colo.	229,000	14	145	1.15	1.9
With tributary valleys	.....	1,100,000	14	145	1.25	1.8
Cache la Poudre	Colo.	220,000	14	135	1.25	1.8
Sevier	Utah	65,000	8	110	1.3	1.5
Boise:						
Mason Creek	Idaho	13,550	11	155	1.2	1.4
Part of Boise project	.....	49,090	11	155	1.3	1.6

DETERMINATIONS OF WATER REQUIREMENTS

Determinations of the water requirements of irrigation projects may be needed both in advance of construction in order to provide the necessary water supply and after completion in connection

with the planning of betterments, such as storage, or in the establishment of the title to the water use. Title to use of water for irrigation in nearly all irrigated areas in the United States is based on beneficial use. The standards followed in such determinations are usually those of reasonable use under the local conditions.

The numerical illustrations that have been given illustrate the amounts of use that may be required under various conditions. As pointed out in the accompanying discussions, they also emphasize the extent of variations in the amount of use caused by local factors and the necessity of basing determinations of use on such local conditions rather than on general averages.

Records of actual use of any large number of individual users under a canal system having fairly uniform conditions of soil and crops usually show wide variations. Such variations are found in areas where water is scarce and expensive as well as where it is plentiful and cheap. They represent the results of individual variations in ideas regarding irrigation needs and in skill and care in applying water. For similar conditions the use of water by the 20 per cent of the farms using the largest amounts may be nearly double the use by the 20 per cent using the smallest amounts. Reasonable use is generally represented by an amount of use somewhat smaller than the average use. Where water is available, use is seldom less than the amount needed and the average use contains some farms on which overuse occurs.

While the use of water in irrigation is subject to many variable factors which make it difficult to determine a reasonable standard of use, such determinations are required in the proper planning of irrigation systems and in the administration of the use of the limited water supplies of the western states. Failure correctly to forecast the water requirements of lands under new canal systems has led to losses in some cases by constructing canals larger than needed and more often by underestimating the requirements with resulting additional costs for supplemental water supplies. Sufficient experience and information are now available so that water-requirement estimates should be made within a margin of accuracy similar to that obtained in estimates of the available water supply.

An estimate of the water requirement of an irrigation system can be assembled by a consideration, first, of the factors affecting the net use, followed by estimates of the conveyance losses. An

estimate of the net use requires a forecast of the types of crops to be grown. While individual farms may have their entire area in the crop of largest use, on canals covering large areas the average division of crops can be used to estimate the net requirement. Net use is most conveniently estimated in terms of acre-feet per acre per season. Distribution of crops may be estimated in percentage of the total area or in total acres where the area served is known. Seasonal distribution of use should be estimated for each crop type.

Where the soils are fairly uniform, an average value of the net use may be used. Where the soil variations are sufficient to affect the use, determination of the extent of the different soils should be made with estimates of the net use for each type.

The results of estimates of the details of use can be combined to give the resulting total demand by months. Such monthly estimates are usually adequate. For critical periods, half months or occasionally weekly demands may be used. While such a method of estimating water requirements involves much detail, it represents a consistent use of the factors that affect the actual practice and is essential if the resulting estimate is to approach the actual use correctly.

Estimates of conveyance losses can be similarly built up, based on the length and size of canals and the character of construction. A more detailed discussion of the factors affecting conveyance losses is given in Vol. II of this series.

Where estimates of water requirements are made for systems in advance of their construction, the rates of use are of necessity based on experience in other areas. Care should be used to see that the results of other experience so used are from areas in which the conditions are comparable. Where estimates are made for existing systems for purposes of water-supply betterment or legal determinations, the actual experience on the local area is available. Some adaptation of past records of use on a canal system may be needed in estimating its future needs. The effect of changing ground-water conditions in either reducing or increasing use should be considered; future crops may differ from those of the past and the average practice usually tends to improve as lands are more carefully prepared for irrigation.

The water requirements of projects are usually based on the needs for delivery to the lands including reasonable surface waste and deep-percolation losses. Where such losses can be

recovered for reuse within the area served, the requirement will approach the value of the consumptive use. Deep-percolation losses usually require artificial drainage for their removal. In the past such drainage has usually been discharged from the area from which it was collected without reuse. In recent years, drainage by pumping has come into use on a number of systems. Where such drainage pumping is delivered into the canals for reuse in irrigation, the diversion requirements are correspondingly reduced. The conditions for such recovery and reuse, both physical and economic, should be considered in planning the water supply of any irrigation system.

References

1. DEBLER, E. B.: Use of Water on Federal Irrigation Projects, *Trans. Amer. Soc. Civil Eng.*, vol. 94, p. 1195, 1930.
2. BARK, D. H.: Experiments on the Economical Use of Irrigation Water in Idaho, *U. S. Dept. Agr. Bull.* 339, 1916.
3. HARRIS, F. S.: The Duty of Water in Cache Valley, Utah, *Utah Agr. Exp. Sta. Bull.* 173, 1920.
4. FORTIER, S.: Irrigation Requirements of the Arable Lands of the Great Basin, *U. S. Dept. Agr. Bull.* 1340, 1925.
5. ———: Irrigation Requirements of the Arid and Semi-arid Lands of the Missouri and Arkansas River Basins, *U. S. Dept. Agr. Tech. Bull.* 36, 1928.
6. ———: Irrigation Requirements of the Arid and Semi-arid Lands of the Southwest, *U. S. Dept. Agr. Tech. Bull.* 185, 1930.
7. ———: Irrigation Requirements of the Arid and Semi-arid Lands of the Columbia River Basin, *U. S. Dept. Agr. Tech. Bull.* 200, 1930.
8. California Division of Engineering and Irrigation, Irrigation Requirements of California Lands, *Bull.* 6, 1923.
9. ———: Flow in California Streams, *Bull.* 5, 1923.
10. Consumptive Use of Water in Irrigation, Progress Report of the Duty of Water Committee of the Irrigation Division, *Trans. Amer. Soc. Civil Eng.*, vol. 94, p. 1349, 1930.

CHAPTER VI

PREPARATION OF LAND FOR IRRIGATION AND METHODS OF APPLICATION

The application of water to land, by the usual methods of irrigation, requires that the land be prepared to permit the uniform distribution of water. Irrigable land varies in its smoothness and regularity of slope and in its adaptability to irrigation. When prepared for irrigation, the slope should be smooth, free from depressions in which water will collect and from knolls which cannot be adequately covered by the water.

Lands on the floor of large valleys usually have smooth surfaces with regular slopes well adapted to irrigation. For loose sandy soils subject to wind drifting the topography may consist of ridges, knolls, and depressions. In the upper parts of large valleys, in small valleys, in foothill areas, and on the bench lands along streams, the action of rain and running water may result in irregular rolling land, cut by channels and gullies.

All methods of irrigation require clearing of the land of its native vegetation. The smoothing and leveling of the surface and the construction of the distribution system vary with the method of irrigation used. The equipment used for land leveling is similar for all methods of application. As the conditions of topography, crop, soil, and permissible costs vary widely throughout the irrigated areas, a number of different methods of irrigation have been developed, each of which has its field of usefulness.

CLEARING LAND

Land cleared for irrigation may require the removal of trees, brush, sod, or cobbles. Dry-farmed land which may be placed under irrigation requires no further clearing. Timber is not a usual growth on irrigable lands, as moisture conditions resulting in its growth are such that irrigation is not usual on such lands when cleared. Some clearing of timber is required for areas along streams, or in areas of large winter precipitation where summer rainfall is lacking. The usual vegetation on the arid and semi-arid lands prepared for irrigation consists of some of the varieties

of brush (Fig. 36). Sufficiently dense sod to be a factor in proper land preparation may occur on low lands or in the Great Plains areas having well-sustained early summer rainfall. Cobbles occur on lands adjacent to streams or on some types of residual soils.

The most common forms of brush are sage brush, greasewood, chaparral, scrub oak and pine, mesquite, and cactus. Native vegetation is adapted to its environment and different types of growth frequently serve as an indication of the soil conditions. Sage brush indicates lands of generally good quality; greasewood occurs more often on lands of heavy texture and larger alkali content. Various alkali-resistant plants indicate the amount and concentration of alkali. The native vegetation is frequently used

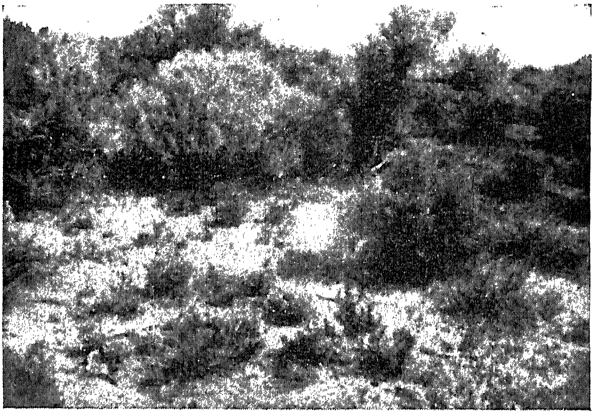


FIG. 36.—Typical native vegetation of sage and rabbit brush on irrigable land.

as the basis of judgment regarding the quality of irrigable land and, when correlated with local experience, is a useful aid in land classification.

Small brush up to 18 to 24 in. in height may be removed by plowing. Larger brush may be plowed but the difficulty of handling the equipment on the brushy areas reduces the economy of this method. Following plowing, the brush requires pulling and raking for burning. Usual contract prices for such work have been about $3.00 per acre for plowing, plus $1.50 per acre for collecting and burning. Hand clearing for brush of medium size and not too dense stand may be contracted for about $5.00 per acre. On land smooth enough to flood without leveling, sage

brush may be killed by irrigation and burned. This method requires a longer period for clearing and is applicable only where time for its use is available.

A method of removing brush frequently used is that known as "railing." A railroad rail 12 to 16 ft. long is dragged across the land, usually in both directions. The brush is broken off or torn out and piled and burned. This method is best adapted to use when the ground is dry or frozen. Power is attached to each end of the rail. Sometimes the rail is bent to a V-shape to give more power in breaking and pulling out the brush. Railing and burning may cost $2.50 to $4.00 per acre.

Clearing loose stone and cobbles consists of hauling away the stones large enough to interfere with cultivation. The stones removed may be used for building rock-wall fences or dumped on unused land. Costs may amount to $25 to $50 per acre or even higher where much stone has to be removed. Stony lands may be used for pasturage without requiring such clearing.

With lands in heavy sod the tufts of broken sod interfere with final smoothing of the surface and preparation of the seed bed. Such lands are usually kept in annual crops for 1 to 2 years before completing their preparation for irrigation. Contract prices for breaking sod lands are usually $3 to $5 per acre.

Sandy soils subject to blowing are expensive to handle.[1] Sufficient wind movement to cause blowing, particularly during spring months, occurs in many irrigated areas. Only limited areas should be exposed to wind action at any time; these should be prepared and seeded to a quick-growing crop such as rye. Alfalfa may be seeded in the young rye or after its harvest in the stubble. Disking in straw reduces or prevents blowing and enables a stand to be secured under usual conditions. Where the land is generally smooth, it may be cleared and leveled in alternate strips, the uncleared strip serving as a windbreak for the cleared strips. After the crop is established on the cleared strips, the remaining area is cleared and seeded. Listing the soil at right angles to the prevailing winds is often used where sandy lands are left without crop. Blowing occurs most readily from smooth soil surfaces. Any roughness such as listing or straw may reduce the wind velocity in contact with the soil below that required for movement.

Stump Removal.—Several methods are used for the removal of stumps on logged-off land. Such lands may furnish pasturage

for at least part of the year without requiring the removal of the stumps. For cultivated crops the roots need to be removed to below the depth of plowing. Stumps up to 6 to 8 in. in diameter are economically removed by hand grubbing. Stump pullers operated by horses or by donkey engines are also used.[2] For large stumps, splitting with powder and pulling the pieces separately is usual. Land containing stumps up to 24 in. in diameter can be cleared with pullers and powder for \$50 to \$150 per acre. In the northwest, with dense stands and large numbers of stumps, per acre costs may exceed these amounts. An engine stump-pulling outfit costs \$4,000 to \$5,000 and is economical only where sufficient areas are to be cleared to justify the cost of equipment. Such outfits are more usually owned by clearing contractors.

Lands containing 30 or more stumps per acre varying from 2 ft. to as large as 8 ft. in diameter are more economically cleared by burning. Some method by which the fire works into the body of the stump and into the roots is required. The char-pit method consists of clearing the bark from around the stump at the ground line, piling chips and bark around the stump, starting the fire, and covering with soil so that combustion takes place under conditions of deficient draft with burning or charring through the stump. This method requires soil heavy enough to bake on heating and drying so that the seal will not be lost. To aid in the burning, holes may be bored through the stump or it may be cut above ground and the upper portion lifted to permit access of the heat to the center. Other methods of burning consist of the use of stump burners by which a hole is burned through the stump which is then charred from the center by maintaining the fire in the hole burned through.[3] Burning methods, while slow, do not require expensive equipment and are adapted to use as time may be available from other activities. Burning methods cost from \$10 to \$75 per acre. Clearing by burning should not be undertaken for 3 or 4 years after logging off, as green stumps are difficult to burn.

LAND LEVELING AND SMOOTHING

The object of this operation is the shaping of the surface to permit the application to the land of water supplied from the system of field ditches. On well-leveled land the water will be easily and uniformly distributed over the land and the waste of

water will be a minimum. When the leveling is poorly done, leaving the surface rough or irregular, more labor will be required to distribute the water, low spots will receive an excess and high knolls a deficient supply, some parts of the land will receive more water than others with a loss by deep percolation, and there will be increased costs, waste of water, and unequal and reduced crop yields. The added expense of careful leveling is more than repaid by the results obtained. This is generally recognized and the tendency of irrigation practice is toward more thorough work in land preparation.

Cost limitations require that the method of irrigation be adapted to the land surface so as to reduce the extent of leveling required. Land leveling should be preceded by the planning and location of the distribution system and arrangement of field areas. Such planning, when carefully done, will result in fitting the irrigation system more closely to the original topography with reduced amounts of grading.

On all except evenly sloping land, a topographic map is essential to careful planning for methods involving shaping the land into check areas of continuous slope or into leveled basins. Such maps should be on a scale of 100 to 200 ft. to the inch, with a contour interval of 6 in. to 1 ft. The cost for mapping will vary from \$0.50 to \$2.00 per acre, depending on the area to be covered and the roughness. The cost of mapping is only a small percentage of the cost of preparing land. Such a map will save much more than its cost on rough land in the reduced cost of leveling resulting from its use.

The amount of grading required and the equipment used will depend on the character of the soil, the topography, the method of irrigation, and the area to be prepared. Land with a subsoil differing from the surface soil cannot be heavily graded without resulting in a variable surface. Such variations may consist of the exposure of hardpan, coarse soil, or tight clays having different fertility and moisture properties from the surface soil with resulting spotted yields and variable irrigation requirements.

Equipment used for land leveling has passed through the same stages of development as that used for other farm operations. Earlier types were adapted to use with the smaller number of stock usual in other farm work. Larger types of horse-drawn equipment led to the use of tractor-drawn implements. Such power equipment tended to larger horsepower in the earlier years

of its use. More recently development has been largely toward lines of equipment adapted for use with the smaller tractors used permanently on the farms with 50- to 75-hp. outfits used for large areas or heavy work.

The most generally used implement is the Fresno scraper (Fig. 37). This is used in two- or four-horse sizes where horse-drawn. The Fresno scraper is inexpensive and can be used for all classes of earthwork on the farm. It is a part of the permanent equipment of many irrigated farms. It may be used for light or heavy cuts and fills and is economical for hauls up to 500 ft.

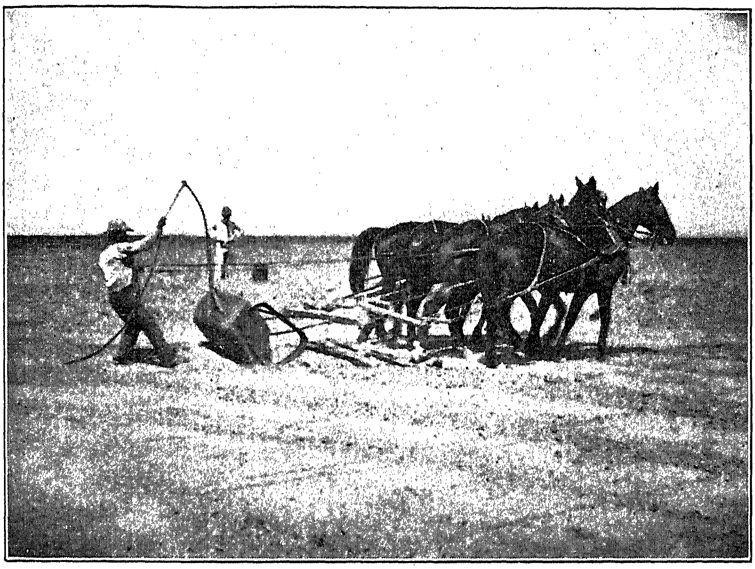


FIG. 37.—Leveling the land surface with Fresno scraper.

There are also a number of levelers similar to the Fresno scraper arranged to be tractor-drawn and operated from the front by the tractor driver through levers or lines (Fig. 38).

Where the grading consists of smoothing undulations or hummocks with short hauls, a commonly used implement is some form of the buck- or tail-board scraper (Fig. 39). It is best suited to sandy soils and is extensively used for such lands. It consists of a scraper board about 2 ft. wide, shod on the cutting edge with a steel plate, and a tail or foot board with the necessary lever arrangement for regulating the angle of the scraper board

and holding it in position. The length depends on the power used, 8 ft. being usual for 4 horses, and 16 ft. for 12 head.

For land consisting of hog wallows or sand-blown hummocks around the clumps of native vegetation where leveling is limited

FIG. 38.—Tractor-drawn and operated Fresno type of land-leveling equipment. (*Courtesy of H. C. Shaw Company, Stockton, Calif.*)

to short hauls in smoothing the surface, a useful implement is the rectangular scraper or leveler (Fig. 40). The size is adjusted to the power available. Its effectiveness is proportional to its

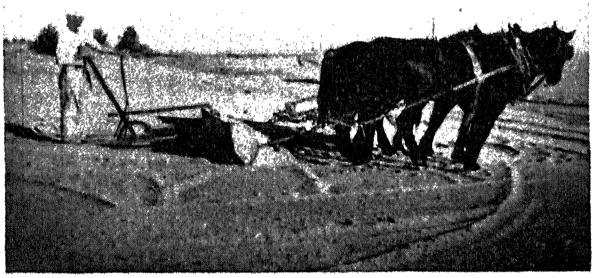


FIG. 39.—Buck or tailboard scraper. (*Courtesy of Bureau of Agricultural Engineering, U. S. Department of Agriculture.*)

length, as a short length merely serves to smooth the surface of the undulations without planing to an even slope. A usual size is 30 ft. long by 12 ft. wide with six crosspieces or scrapers, all

of 4 by 12 timber well braced and securely fastened. Cutting edges are faced with ⅜-in. steel plates. One crosspiece may be adjustable by levers so that the weight may be thrown on it for additional cutting force on high areas. Such a leveler weighs

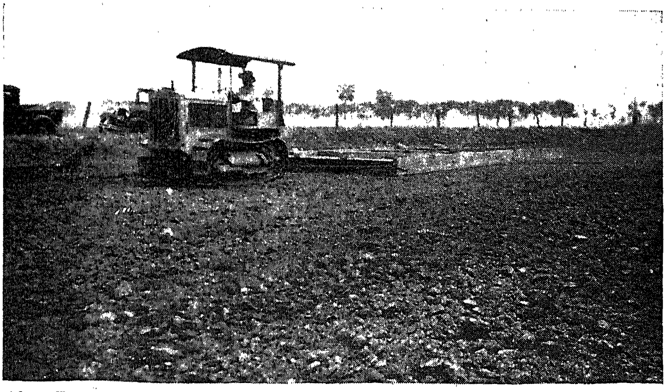


FIG. 40.—Rectangular land leveler. (*Courtesy of Bureau of Agricultural Engineering, U. S. Department of Agriculture.*)

nearly 2,000 lb. and requires 16 horses or a tractor for its operation.

A larger size of similar leveler with wheel traction is shown in Fig. 41. This is drawn with a tractor, the tractor operator

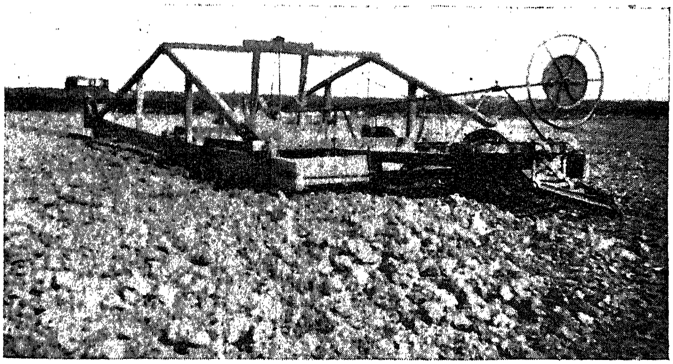


FIG. 41.—Large braced rectangular leveler with wheel traction.

adjusting the cut for the main cross blade by use of the wheel which projects within reach of the tractor seat. A combination steel leveler and scraper for use with tractors is shown in Fig. 42.

For final finishing of the surface, various forms of floats are used (Fig. 43). Such floats are used for preparation of the seed

bed when crops are changed on land after its original preparation for irrigation. They are usually made in sizes adapted to the use of the same power used in plowing. Floating does not move earth to any extent but smooths and compacts the surface. Floats are sometimes loaded to give added effect in compacting.

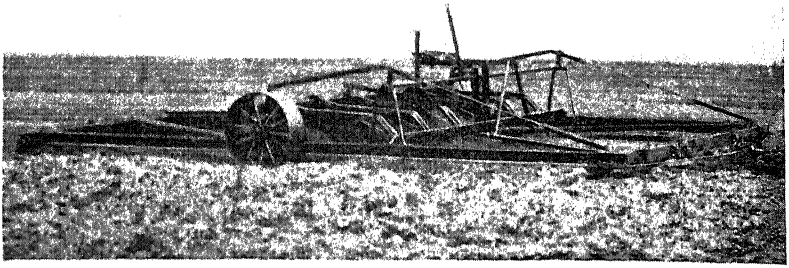


FIG. 42.—Leveler and scraper with steel frame. (*Courtesy of Eversman Manufacturing Company, Denver, Colo.*)

Road graders are sometimes useful in leveling land into checks where the earth is crowded into the field levees in the same way that earth is crowded into the crown of the road. By setting the blade at right angles to the direction of travel, a road grader becomes a single-blade leveler.

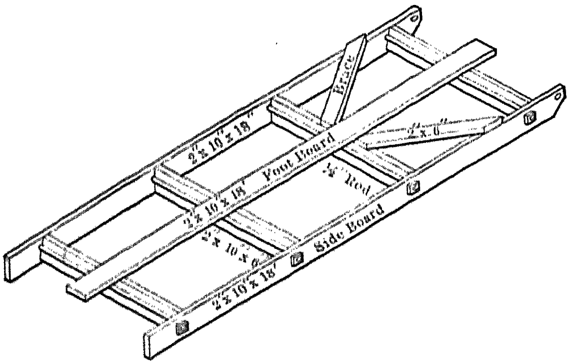


FIG. 43.—Float for smoothing land surface.

Heavier equipment includes wheel traction graders of the enlarged Fresno scraper type drawn by large tractors. These may handle 3 to 4 cu. yd. of earth per load. This size requires power operation of the scraper, lifting or tilting being controlled by power transmitted from the tractor. Push graders of the

bulldozer type are also sometimes used in irrigation leveling for rough grading.

Land leveling for irrigation is an operation required usually only once for an irrigated farm. For the average size of individual farm, the purchase of heavy equipment is not justified. Much land leveling is handled by contract with the landowner. Some lands have been prepared for irrigation prior to colonization. Contracts for land leveling can be brief and simple in form. The land to be leveled, the kind, size, slope, and location of checks, the levee work to be done, the location and extent of ditches to be built and the kind, number, and location of structures are included. The contract may cover land grading only, leaving the finishing and distribution system to be built by the landowner.

Land-leveling contract prices are based on costs per acre. For the large number of cuts and fills required, determination of the earth moved in terms of cubic yards is impractical. While the finished elevation of the land may be definitely specified, it is not practical to bring the surface to an exact level or slope. For good land leveling, variations above or below the planned grade should not exceed 1 to 1½ in. The best method of determining the character of the work is by an actual irrigation. This settles the fills and shows the high and low spots. By following such an irrigation promptly with the finishing leveling, the initial crop can be planted so as to utilize the moisture from the trial irrigation. The opportunity for disagreement regarding the final finish of land leveling makes the protection of the landowner rest more fully in the dependability of the contractor than for many other types of work. In order that the owner may have the finishing work continued to his satisfaction without controversy with the contractor, some leveling is handled on a daily rental basis for the use of the equipment.

The cost of land leveling varies widely. Land of even slope which requires only minor smoothing may be prepared for \$3 to \$5 per acre in addition to the cost of clearing and of the distribution system. Where cross slope is removed from checks but where little general grading is required, costs may be \$8 to \$10 per acre. Where depressions are filled and knolls leveled down, the cost increases rapidly with the amount of grading required. Costs of \$20 to \$30 are usual for such land. Some lands have been leveled at costs of \$50 to \$100 per acre. While an owner may spend large costs per acre on a portion of his land in order to

avoid waste areas, lands requiring expensive general leveling should not be purchased except with proper allowance in the price for such cost and the generally lower average yields obtainable for the first few years of use.

METHODS OF APPLYING WATER TO LAND

No one method of irrigation is adapted to all of the conditions found in different irrigated areas. Of the several methods in use, some are of general application, while some require special conditions. Table XXII lists the methods in sufficiently wide use to justify descriptions, using the name more generally applied to each method with an estimate of the relative extent to which each method is used. There are no definite statistics of the area served by each method and the estimates used in the table are based on general information regarding the practices in each state. As the conditions in California result in the more extensive use of some methods not generally adapted to the conditions in other states, a separate estimate for it is included.

TABLE XXII.—ESTIMATED PERCENTAGE OF TOTAL AREA IRRIGATED FOR WHICH THE DIFFERENT METHODS OF PREPARING LAND ARE USED

Method of irrigation	All states except California	California	All states
Wild flooding	50	10	40
Border checks	7	23	11
Rectangular checks	3	5	3
Contour checks	6	10	7
Furrows:			
Orchard and row crops	22	35	25
Corrugations	8	....	6
Orchard basins	1	5	2
Orchard contour furrows	0.5	1.5	1
Surface pipe	0.5	5	2
Sub-irrigation	2	5	3
Sprinkling	...	0.5	

Wild flooding was generally used for all flooded crops until economic conditions justified the costs of the various methods of checking land. In those areas where conditions permit checks to be used, there is some tendency toward a reduction in the area wild-flooded. In some of the mountain states nearly all of the

area except that in furrow crops is wild-flooded. Checking methods are more generally used in the more southern irrigated states, where the longer seasons and greater number of irrigations make the saving in labor costs of applying water of larger relative importance. Furrows are used for orchard and row crops; a type of furrow practice, usually called "corrugation," is used in some areas for forage and cereal crops. Basins, either rectangular or contour, are used in some orchard practice and on steep lands orchard may be planted on contours and irrigated with contour furrows. The surface-pipe method is a special method of flooding; sub-irrigation is practiced in delta areas in California and under some conditions in other states. Sprinkling for commercial crops is used to a limited extent in California and in the eastern states.

WILD-FLOODING METHOD

In the wild-flooding method, water is distributed from field ditches from which it flows over the ground, guided only by the slope of the land. The field ditches are located so as to reach all controlling elevations and are spaced so that in flowing from one ditch to the next, the water will cover all of the cropped area. Other names used to describe the same method are flooding from field laterals and free flooding. This method is the prevailing one for other than furrow or row crops in the mountain states. While the water is more difficult to control than in the various check methods of flooding, it requires little expense for land preparation and can be adapted to steep or rough lands. Its principal disadvantage is the small head or stream which an irrigator can handle with the consequent large labor cost per irrigation. On this account, wild flooding is better adapted and more generally used in areas of relatively short growing season where not over two to four irrigations per season are needed.

With the wild-flooding method, the distribution system consists of permanent-supply ditches, located along the higher boundaries of the field or on the ridges, and of field ditches placed at as regular intervals in the field as the topography will permit. Each field ditch serves a strip of land on one or both sides of the ditch, the water being checked in the field ditch by temporary dams and turned out through cuts in the ditch bank so that the land is fully covered as the water moves down the slope. With such annual crops as grain, the field ditches are usually made

after seeding and plowed in before harvest. For permanent crops, such as alfalfa, the field ditches remain during the life of the stand, the crop being harvested separately for the area between the ditches.

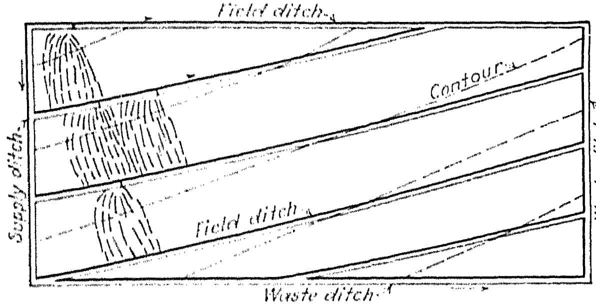


FIG. 44.—Wild flooding with field ditches on flat grade.

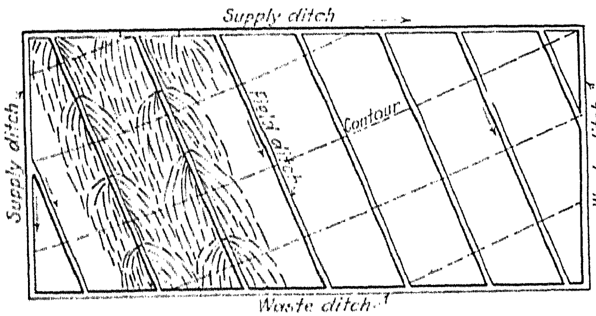


FIG. 45.—Wild flooding with field ditches on steep grade.

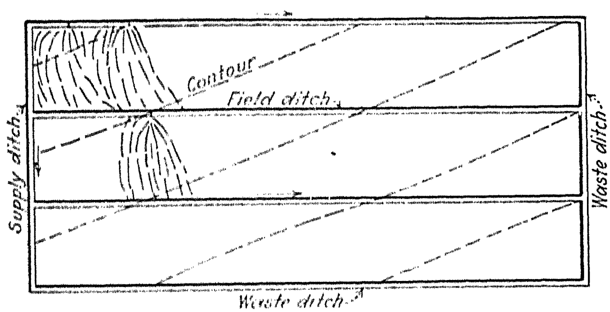


FIG. 46.—Wild flooding with field ditches at right angles to sides of field.

Three general systems of arrangement of field ditches are used. These are illustrated for regular topography in Figs. 44, 45, and 46. In Fig. 44 the supply ditches are located along the margin of the field and the field ditches extend nearly parallel to the

contours so as to have a relatively flat grade. The water diverted on to the land flows at right angles to the field ditches. With this method the field ditches may be placed 100 to 200 ft. apart on usual slopes without having excessive percolation losses near the points of turnout. Wider spacing is used on the heavier soils. Excess water or surface waste collects above the bank of the next lower ditch and may move along its bank to the waste ditch or be taken into the lower ditch and distributed on lower land.

In Fig. 45 the supply ditches are located across the field on a flat grade with the field ditches at right angles to the contours. Water is diverted on to the land from both sides of the field ditches. As the water tends to follow along the field ditches rather than to spread laterally, closer spacing is usual, varying from 60 to 80 ft. on flat slopes to 40 to 60 ft. on steeper land. Waste water works down the length of the strip.

Figure 46 illustrates an arrangement of field ditches at right angles to the sides of the field, which gives intermediate grades to the ditches and rectangular field areas. Water flows down the steepest slope diagonally to the direction of the ditches. The spacing of the field ditches is intermediate in amount to that used for the two other arrangements; spacings of 80 to 150 ft. would be typical. Waste water can be picked up in the lower ditches or will collect at the low side of the field.

While Figs. 44, 45, and 46 illustrate the applications of the three types of field ditches on lands of regular slope, the same methods are applicable to uneven land. On steep land, closer spacing is needed to give more complete control; for such lands the field ditches should be run on a flat slope with spacings of 50 to 60 ft. On coarse soils, closer spacings are needed; on sandy lands, water should not be run over the ground for more than 60 to 80 ft. with the small sizes of heads usual with this method. On medium soils, the spacing of field ditches should be adjusted so that sets of not over 1½ to 2 hr. will cover the area served from each set; longer sets result in large deep-percolation loss on such soils. By proper adaptations, the wild-flooding method can be used on any soils or slopes that are irrigated. It is best suited to medium soils on slopes of 6 to 12 in. per 100 ft. On heavy soils, it is difficult to avoid excessive waste; on coarse soils the small heads used make it difficult to avoid excessive deep-percolation losses. Wild flooding is used on slopes up to 10 per

cent, with occasional areas as steep as 20 per cent. On steep lands, shallow furrows are used for the first irrigations until the crop can protect the soil from erosion. These markings are partially retained in much wild-flooded land, giving a mixture of wild-flooding and furrow practice.

Attendance on irrigation during the night is sometimes not continuous with the wild-flooding method, so that the handling of night sets is an essential element in the field-ditch layouts. With ditches down the steepest slope, night sets can be started at the head of the field. Surface waste may not occur before morning. Any missed areas can be covered from the field ditches during the day. With the two other arrangements of ditches, openings for waste in the upper banks of the lower ditches will be needed, with dams for the rediversion of the waste. The breaking of dams in the night may result in large loss by waste through the ditches.

Where the water is allowed to run without attention during the night, measurements show larger average depths of water applied than where more frequent changes are made. For good results in wild-flooding practice, at least one or two night changes should be made. Continuous night attendance is used in the better practice, particularly where large heads are handled.

Field ditches in the wild-flooding method occupy widths of 5 to 8 ft. and may reduce the cropped area by 4 to 6 per cent, depending on the ditch spacing used. This is larger than the similar lost cropped area with other methods of flooding.

Although the irrigator in some wild-flooding practice may handle the water for the full 24 hr. of the day, using night sets and making changes as needed during the daytime, the labor cost of application by this method is relatively large owing to the small stream handled. The labor involved is greater than with the methods of guided flooding in checks. However, the extensive use of this method indicates that its advantages in low first cost of preparation balance its disadvantages. While other methods are replacing wild flooding on some of the flatter lands on which it was formerly used, a considerable part of the area now wild-flooded is not well adapted to the other flooding methods and wild flooding will continue to represent an important part of irrigation practice.

Few permanent structures are used in wild flooding.[4] Division boxes or check gates used on the supply ditches may be perma-

nent. For field ditches, temporary canvas, steel, or earth dams are used. The canvas dam (Fig. 47) is held in place by earth around its edges and the weight of the water. Steel dams

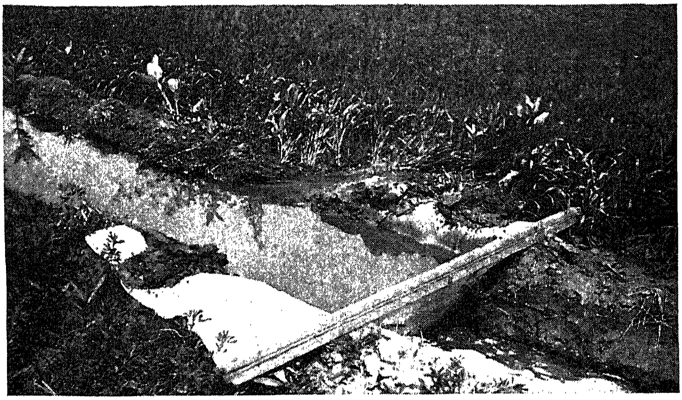


FIG. 47.—Use of canvas dam in field ditch. (*From Fortier and Lewis.*[11])

(Fig. 48) are forced into the sides and banks of the ditch. Earth dams may be built from dirt shoveled from the bottom of the ditch downstream from the dam or scraped from the ditch by horse-drawn jump shovels. When the earth dam is broken,

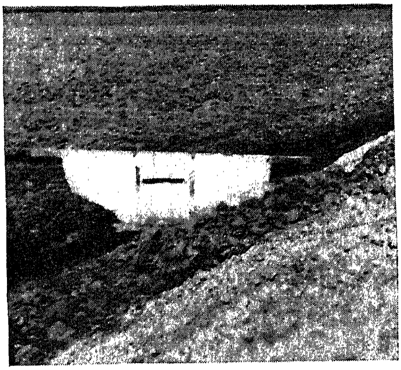


FIG. 48.—Steel dam in earth ditch.

much of the earth may wash back into place, but such dams result in gradually deepening the ditch. Steel dams are not well suited to ditches of uneven size or for gravelly ground.

Water is applied by turnouts from each field ditch above the temporary dams. The turnouts are distributed so that the full area is covered. Spacing of turnouts varies from 20 to 60 ft., depending on the slope of the land and arrangements of the field ditches. For the larger sizes of irrigating heads, more than one field ditch may be operated at a time. The size and grade of ditches are discussed in Chap. VII.

The heads handled vary from 1 to 4 or 5 sec.-ft. On medium soils for usual conditions, heads of $1\frac{1}{2}$ to $2\frac{1}{2}$ sec.-ft. give the best results. With smaller heads, the water moves slowly and deep percolation occurs near the field ditches. Larger heads are more difficult to control and surface waste is often large. With lighter soils, somewhat larger heads are preferable. The average depth of individual irrigations in the better wild-flooding practice is about 6 in.

BORDER METHOD

The border method of checking land for irrigation consists of long narrow strips, extending lengthwise down the natural slope and separated by parallel levees or borders which confine the flowing sheet of water within the strip as it runs down the slope. Water is delivered into each strip from a field ditch at its upper end.

This method is an improvement on the wild-flooding method in that, by guiding the flooding by the field levees, larger streams can be handled and longer lengths of run over the ground used without excessive percolation losses. The cost of preparation for border checks is higher than for wild flooding but the cost of applying water is materially less.

Other names used in some localities to describe the same method are "strip checks," "ribbon checks," and "gravity checks." Strip and ribbon checks refer to the shape of the field areas; the term gravity check is used to distinguish these sloping checks from the level areas of rectangular or contour checks. Border checks are usually run parallel to the side of the field rather than at right angles to the contours in order to secure uniform lengths and arrangements of the checks and to avoid small corner areas.

Checks in the border method are made level transversely, so that the water will flow over the whole width at even depth. The slope longitudinally is continuous and preferably uniform;

variations in the rate of slope are used, however, in preference to incurring the cost of grading to a uniform slope for the entire length. Where the slope varies, the steeper grade should occur on the lower portion of the check. Flat grades on the lower end, where the remaining head available is reduced by the percolation on the upper end, will result in slower progress of the water and excess depths of application. If marked differences in the rate of slope occur, the lengths of the checks should be adjusted to the topography so that the widths and sizes of head may correspond

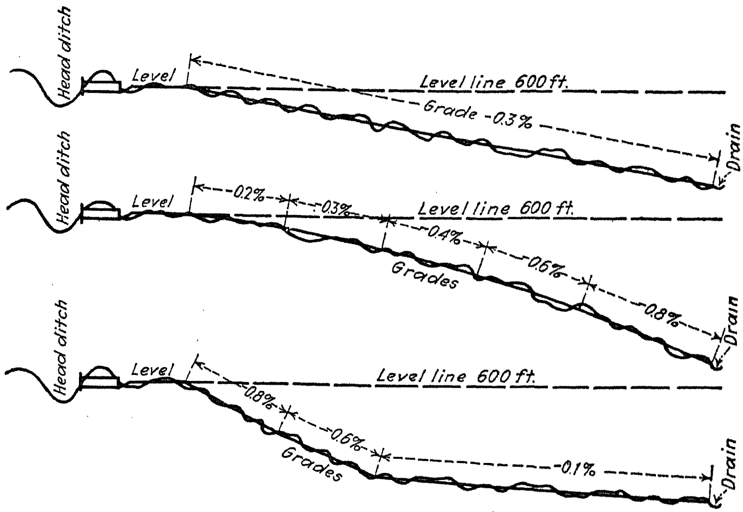


FIG. 49.—Profile of typical border strips showing surface before and after grading. (*Fortier.*[5])

to the slope. It is good practice to make the upper 20 to 30 ft. of the check level, so that the stream may spread evenly across the width of the check before the flow starts down the slope. Part of the earth from such leveling can be used in the banks of the supply ditch; on steep slopes or heavy soils low cross ridges may be used in the checks to reduce the velocity of flow down the check.

The adjustment of the slope to fit the land without excessive grading is illustrated by Fig. 49. The two upper profiles represent more desirable slopes than the lower profile.

Desirable slopes for border checks vary from 2 to 8 in. per 100 ft.. Slopes as flat as 1 in. per 100 ft. or as steep as 2 to 3 ft. per 100 ft. may be used but require adjustments in size of check and heads that may lose the advantages of the border method. Narrower

checks are used on the steeper slopes. Shorter checks are preferable on both flat and steep slopes than on medium grades. Short checks on steep slopes permit readjustment of flow with less danger of erosion. For heavy soils, slopes from 1½ to not over 4 in. per 100 ft. are desirable; on medium soils the similar range is from 2 to 6 in.; while for sandy soils desirable slopes vary from 4 to 8 in. per 100 ft.

The relative width and length of border checks vary but the check is always a long narrow strip. Usual ratios of length to width vary from 6:1 to 15:1. For small heads, checks as narrow as 24 ft. may be used. Formerly checks 80 to 100 ft. in width were used with large heads; more usual present practice does not exceed 50 to 60 ft. with some 66-ft. widths. Lengths vary from 200 ft. on steep or sandy land with small heads to 1,320 ft. on flat slopes of heavier soil. More usual lengths do not exceed 660 ft. Many 40-acre fields are divided into three or four lengths of 440 or 330 ft.; the tendency of present practice is toward shorter lengths and more careful control of the water.

Table XXIII represents the recommended practice regarding the combinations of size of head and soil for principal soil types for California conditions.

TABLE XXIII.—SIZES OF BORDER CHECKS[6]

Head of water delivered to each check, second-feet	Soil types					
	Sands		Loams		Clay	
	Width, feet	Length, feet	Width, feet	Length, feet	Width, feet	Length, feet
1	20 to 30	200 to 300	30	300 to 400	30	440 to 660
1 to 2	30 to 40	300 to 400	30 to 40	440 to 660	30 to 40	660
2 to 4	30 to 40	440	40	440 to 660	50	660 to 800
4 to 8	40	440 to 600	50	660 to 880	50	880 to 1,320

The size of stream handled varies from as small as 1 sec.-ft., where water is obtained from wells of limited capacity, to 15 to 20 sec.-ft. under canal systems for lands well adapted to this method. For small heads the size of check is reduced and the entire flow used in one check at a time. For large heads three or more checks may be irrigated simultaneously. In some cases

10 sec.-ft. or more may be turned into a single check but more usually not over 5 to 6 sec.-ft. per check are used. The size of head used varies from 0.05 to 0.2 sec.-ft. per foot width of check. One irrigator may handle the entire stream, continuous attendance being usual with the larger heads. Where a canal system delivers heads of 15 to 20 sec.-ft., the time schedule is usually 30 to 20 min. per acre, so that the time spent in irrigation per farm is usually short. For such large heads, two irrigators are frequently used, one attending to the water in the field and one watching the field ditches. The size of head used per acre of area in a check will vary from 3 sec.-ft. in clays to 10 sec.-ft. in sandy loams and 20 sec.-ft. in gravelly loams. For clay soils 3 sec.-ft. may be used in a 1-acre check, for sandy loams 5 sec.-ft. in a ½- acre check, and for gravelly loams 7 sec.-ft. in a ⅓-acre check.

The border method is best adapted to soils which take water fairly readily so that the desired depth per irrigation may be absorbed from the water as it flows over the land. On heavy soils, waste from the lower ends will occur before the desired depth of absorption has been obtained, unless small heads are used on flat slopes. For medium to light soils the practice should be such that water is delivered into the checks for 40 to 90 min. Longer times of delivery will result in excess percolation at the upper end of the run.

The border method is used on all flooded crops. It has the advantage over flat check methods that, where rotation of crops is followed, the slope and length of the borders may be used for furrow crops without releveling. For rotation to furrow crops the levees may be smoothed down or left with furrows on the levees.

The field ridges or levees should be well rounded and no higher than needed to confine the flow. On well-prepared land of even slope the depth of the flowing water in the check should not exceed 4 to 6 in.; levees of 6- to 10-in. settled height are adequate to control such flow. The side slopes of the levees should be rounded to facilitate movement of crop-handling equipment. A width of 5 to 8 ft. is usual. The area of the levee is not lost from crop production with such levees, as the water will extend well up on the sides of the levee and percolate laterally under its crown. Crop growth on well-made levees should be nearly as vigorous as in the area of the check. Levees may be formed by scraping soil from the surface of the check, working back and forth across the

checks or by the use of checkers consisting of V-shaped drags drawn with the wide end forward, the rear end having an opening equal to the desired width of the levee (Fig. 50). Smoothing floats may be used to finish the levee. Care should be used with all methods to avoid leaving depressions in the check along the levees in which the water may collect and flow, leaving some of the center uncovered.

A system of border checks worked out to fit the topography of the land is shown in Fig. 51. A similar illustration where part of the farm was prepared in border checks is shown in Fig. 52. The arrangement, widths, and lengths of the checks were adjusted to the conditions in the different parts of each tract.

FIG. 50.—Building small levees for border method of irrigation in Idaho. (*Fortier.*[5])

Permanent structures are usual in the ditches for checking the flow and for delivery into each check. One check structure across the ditch may raise the water for delivery into several checks. The side or levee gates delivering into each check may be of wood or concrete. Typical structures are described in Chap. VII. For small heads, canvas or steel dams may be used in the supply ditch and cuts made in the ditch bank for delivery to each check.

Flow into the check is usually shut off somewhat before the water reaches the lower end, the water flowing down the check being sufficient to complete the irrigation. Provision for prevention or removal of waste water should be made at the lower end of

the checks. This may be done by stopping the levees before the lower end is reached, to permit cross spreading of waste water, by a drainage ditch across the lower end of the checks, or by taking the waste into the next lower ditch through the upper-ditch bank.

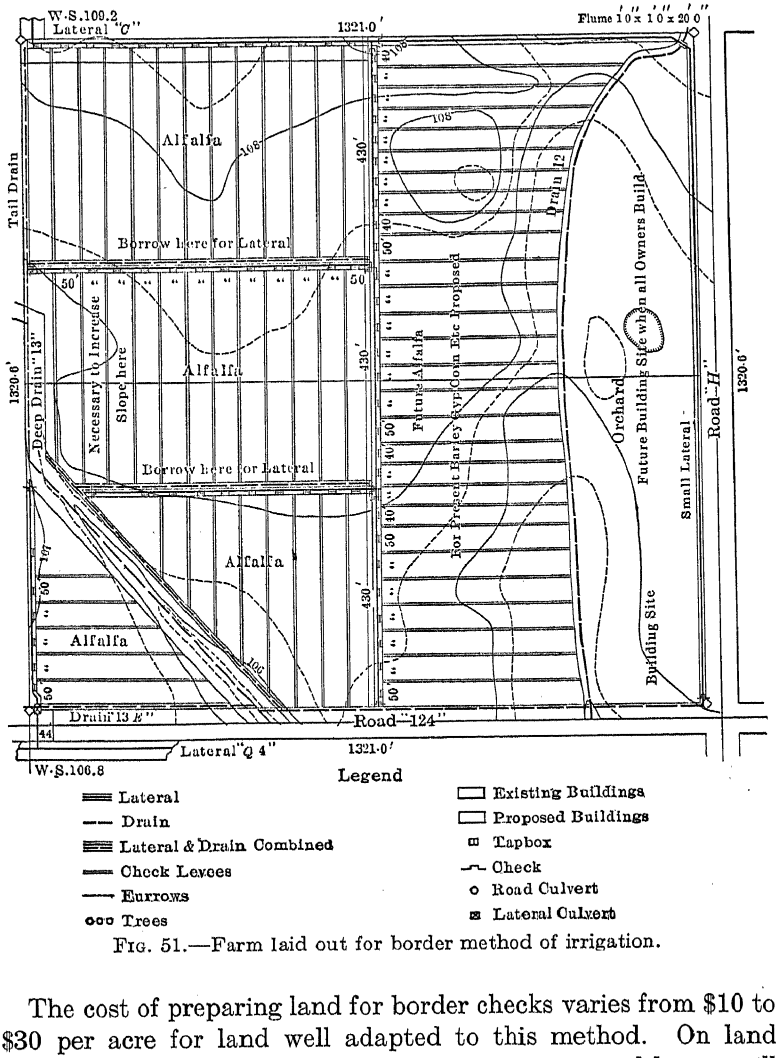


FIG. 51.—Farm laid out for border method of irrigation.

The cost of preparing land for border checks varies from $10 to $30 per acre for land well adapted to this method. On land requiring no general grading, ditches, structures, and levees will cost $8 to $15 per acre. Where grading is required to secure

the desired slope of the checks, this method may cost $50 per acre. Some lands have been prepared by this method at costs as high as $75 to $100 per acre.

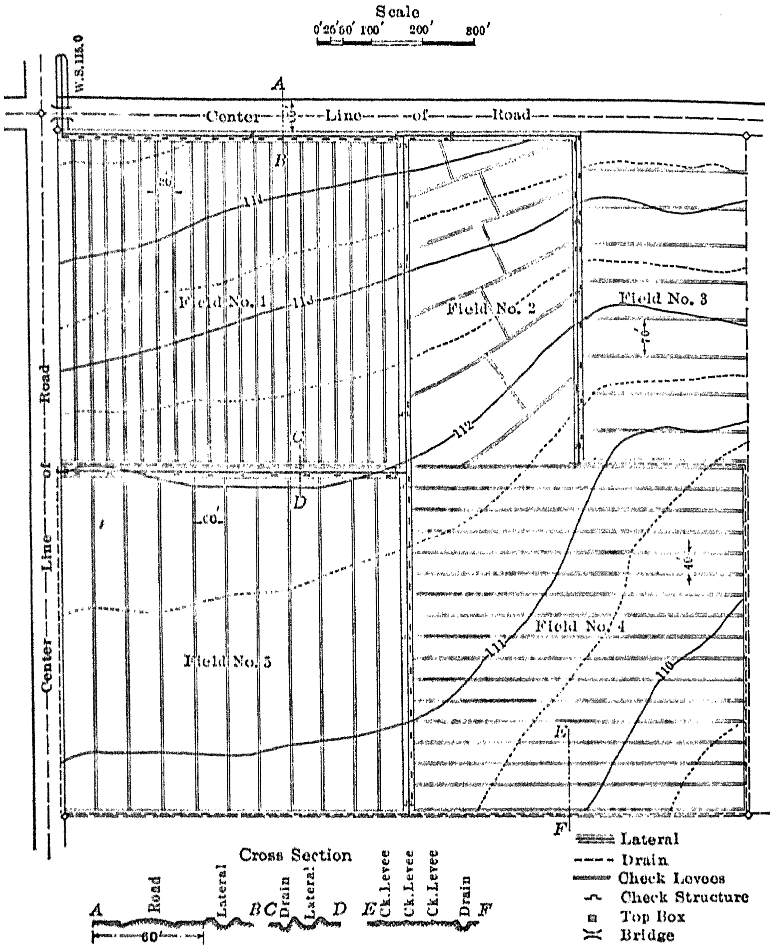


FIG. 52.—Farm plan showing adaptation of border, contour, and rectangular check methods of irrigation.

RECTANGULAR AND CONTOUR CHECKS

Rectangular and contour checks consist of level or nearly level areas surrounded by levees in which the water applied may be ponded until absorbed. The distinction between the rectangular and the contour checks is one of shape. The term "rectangular

check" is used to describe lands prepared in areas which are rectangular in shape and also at right angles to the sides of the field. Contour checks have such shape as the irregularity of the topography may produce. Contour checks may be rectangular where the contours are straight but are not usually called rectangular checks unless the contours are at right angles to the sides of the field.

There are several types of practice for which such checks are used. For the intensively cultivated individual farm the land within the check is leveled with a degree of care similar to that used for border checks. These are the rectangular and contour checks to which most of the following discussion applies. For rice irrigation in California a type of contour check is used which is not leveled within the check. For overflow lands, large areas may be enclosed with levees 2 to 3 ft. high in order to retain overflow flood water for annual crops or pasturage. Differences of elevation of 1 or 2 ft. may occur within such checks. Contour checks when applied to very steep land become a form of terracing. Economic conditions in the United States have not made it profitable to terrace irrigated hillside land as extensively as it has been done in some countries.

Well-prepared rectangular and contour checks are used for any flooded crops. They are also used at times for crops usually irrigated in furrows, such as cotton and sugar beets, where the row crops are grown in rotation with grain or alfalfa. Such checks are better suited to the heavier soils where water may need to stand on the land for several hours in order to secure adequate absorption or on very light soils subject to erosion if irrigated by slope methods. For heavy land the time of ponding should be limited so that scalding of the crop does not occur. Much wind-blown sandy soil has a rough surface but no regular slope. Such lands can be more cheaply prepared in rectangular checks than in slope methods. With properly prepared checks, practically as large heads can be handled as with border checks. Where only small heads are available, checks as small as $\frac{1}{10}$ acre may be used. With large heads the leveling costs control the size except on very flat lands so that usual better practice does not exceed 1 acre per check. For large overflow checks, the sizes of head handled may exceed 50 sec.-ft.

Fields 2 and 3 in Fig. 52 illustrate these two types of checks. Field 2 is prepared in contour checks and field 3 in rectangular

checks. Figure 53 represents a typical arrangement of contour checks with field ditches delivering directly into each check. The resulting irregularity of size of the individual checks illustrates one of the disadvantages of this method. Figure 54 is a well-prepared field in contour checks for alfalfa.

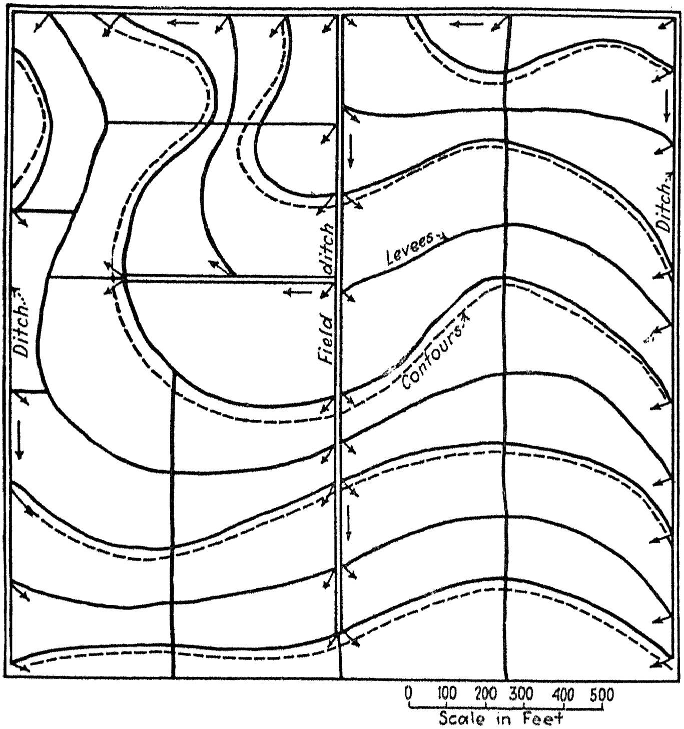


FIG. 53.—Farm laid out for contour check method of irrigation with ditches delivering water to each check.

As the area within each check is leveled, these methods are best suited to land having only slope enough for desirable ditch grades. For steeper lands either narrower checks in the direction of the slope or greater differences in elevation between adjacent checks are required. A grade of 3 to 15 ft. per mile or $\frac{2}{3}$ to 4 in. per 100 ft. is well adapted to such checks. The difference in elevation between adjacent checks does not usually exceed 6 or 8 in. This limits the width of checks to 66 ft. or less on lands having slopes of over 9 to 12 in. per 100 ft. Steeper land is preferably prepared for other methods.

The desirable ratios of length to width may vary from 1 to 1 for square checks to about 4 to 1 on steeper land. Rectangular and contour checks should have smaller ratios of length to width than border checks, as the water does not flow so readily across the flat slope of the checks. On flat lands, square checks have the shortest distance of flow to reach the farthest portion of the check for any given area of check. This results in the use of square checks on much flat land of coarse soil. Such checks may vary from 60 to 200 ft. square, the latter having an area of nearly 1 acre. Greater length in proportion to width results in less frequent spacing of field ditches. Lengths should not exceed 300 to 400 ft. even on impervious soils. Acre checks approxi-

FIG. 54.—Contour checks in alfalfa.

mately 150 by 300 or 100 by 400 or smaller checks having ratios of length from 2:1 to 4:1 are typical.

Water should be delivered directly into each check. Ditches are run down the slope and may deliver into checks on each side, giving a ditch spacing equal to twice the length of the check. On heavier soils, water may be run from one check to the next lower one through boxes in the levees. This may be done in irregular areas to avoid too many field ditches but should be limited to short distances.

Rectangular and contour checks should be nearly level longitudinally. However, as absorption will begin at the inlet end as soon as water is turned in and continue while water is reaching the farther end, it is advisable to make the farther end from 1 to 2 in.

lower than the inlet, so that the difference in depth of ponding may tend to balance the difference in absorption while filling.

Levees for these checks are similar to those used for border checks, except that the levee on the contour includes the difference in elevation of the adjacent checks. Earth for the levee is taken from the high side of the lower check.

A special type of contour check is used in rice irrigation in California (Fig. 55). Levees are run on contours at about 0.3-ft. difference in elevation. The area within the check is not leveled, the cross slope of the check being taken up in the difference in the depth of ponding. Cross levees to divide the length of the checks are not generally used; water is delivered to the highest check in the field and carried from check to check through gates set at intervals in the levees. The rice is grown on soils which are nearly, if not entirely, impervious so that this practice can be used; on usual soils it would result in excessive percolation losses.

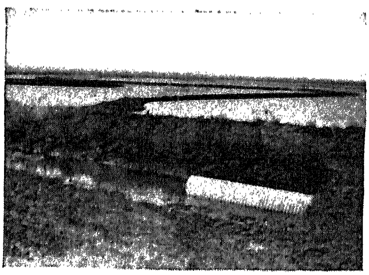


FIG. 55.—Checks for rice irrigation, Sacramento Valley, California.

The cost of preparing land for rectangular or contour checks varies with the extent of cut on the high side and fill on the low side. On land of small and regular slope, the cost may be nearly as small as for border checks on the same land; for irregular direction of slope or for flat lands, rectangular and contour checks will cost less than borders. Unless the contours are straight and at right angles to the field boundaries, rectangular checks require diagonal grading with higher costs than contour checks. Flat land of even surface may be prepared for $8 to $15 per acre; costs of $20 to $50 per acre are frequently required for steeper slopes or irregular surfaces.

BASIN METHOD

The basin method of irrigation represents the special application of rectangular and contour checks to orchards. The checks are made small enough so that leveling within each basin is not required. It is also usual to remove the ridges in the cultivations after each irrigation and rebuild them for the succeeding application. Until recently, most basin checks were rectangular, usually

square, containing one tree; now contour checks containing groups of trees are also used in a number of localities.

For the irrigation of orchards, either flooding in basins or the use of furrows represents the choice usually available. Practice is not clearly divided regarding the conditions for which either of these methods is used. Local custom is frequently a large factor in the practice. In general, basins are used for conditions less well adapted to furrows. These include heavy soils, where the wetting of the partial area in the furrows makes it difficult to secure sufficient absorption, and the porous soils where excess

FIG. 56.—Ridger used in preparing orchards for basin irrigation. (*Courtesy of Division of Irrigation Investigations and Practice, California Agricultural Experiment Station.*

percolation occurs at the upper end of the furrows with limited cross-capillary movement. Steeper lands are not well suited to usual basin practice, although special forms of basin may be combined with contour furrowing or terracing. Basins are more generally used in the southwestern states. In California, basins are more often used in deciduous than in citrus practice. Basin checks enable a larger head of water to be handled than furrows do and have an advantage where it is desired to irrigate an entire orchard quickly at a certain stage of growth. Basins are also used for winter irrigation where moisture storage up to the full capacity of the soil is desired.

While the area of the basins is sufficiently small so that leveling within the basin is not required, it is usual to throw earth toward

the trees in the cultivation so as to protect the trunk from direct contact with the water when the basin is filled. Such contact may be harmful to the trees.

The ridges are made by throwing earth from the sides toward the center. As the soil has usually been cultivated, the surface mulch is used. Double disks, or ridgers, either home or factory made, may be used. Where each basin contains one tree, ridges are made in both directions in the center of each tree row. The breaks made by the cross ridging are closed by hand shoveling, or a jump shoveler may be drawn behind the ridging equipment which is used for this purpose (Fig. 56). Where contour basins are used, the orchard is surveyed on contours at about 0.2-ft.

FIG. 57. Contour basins in orchard in California.

FIG. 58. Basin irrigation of orchard with ditch delivering water to each basin.

difference in elevation, located wherever they may come among the trees. The ridges are then built as nearly along these contours as the position of the trees will permit (Fig. 57). In order to replace such ridges for later irrigations without resurveying, the trees are marked with different colors, the ridges being built on the left or right of all trees having the same color. Cross ridges should be used every four to six tree rows. Such contouring has been mainly applied to old orchards where leveling could not be done. For new orchards some leveling before planting will give more regular basins; if carried far enough, such leveling may approach contour furrowing in appearance.

Two methods of delivering water to rectangular basins are used. More uniform distribution can be obtained by delivery directly to each basin as in Fig. 58. As the ditches are made from the dry surface soil resulting from cultivation, control of the flow requires constant attention. The other method consists of run-

ning water from basin to basin. This may result in excess application in the upper basins. On heavy soils, water may be run from four to six tree rows across basins without material disadvantage. In some practice where permanent basins with summer cover crops are used, the ditches between basins become compact and represent better practice than running water across the basins.

There is little cost for land preparation for the basin method, as land leveling other than the general smoothing that would be needed for cultivation is not required. The ridging for each irrigation costs 50 to 75 cts. per acre.

SURFACE-PIPE METHOD

The surface-pipe method of irrigation consists of the conveyance of water to the individual field areas in slip-joint metal pipe placed on the surface for each irrigation. Water is supplied to the surface pipe from permanent pipe lines. The use of the surface-pipe method is largely limited to irrigation from wells where the pumping lift and pressure for delivery are obtained in one pumping operation. This method resembles the wild-flooding method with the field ditches replaced by the temporary pipe lines. The land does not require checking or leveling except general smoothing, as the water can be conveyed to the undulations or knolls under pressure. The surface-pipe method is particularly adapted to land of somewhat rough surface which has subsoil conditions that prevent the heavy grading needed for other methods and where only small heads are available.

The surface-pipe method is used in the California areas securing water from wells and to a less extent in other areas. It is mainly used for alfalfa on lands requiring only one irrigation per cutting which is applied after cutting, when the crop does not interfere with the handling of the pipe (Fig. 59). It is not adapted to use when the crop is high, owing to trampling and greater labor in handling. Slip-joint pipe may also be used in place of field ditches in basin irrigation of orchards or for delivery into small checks for other crops. Such practice represents a method of delivery of water rather than a method of irrigation. Slip-joint pipe is also made with openings with slide gates along its length for delivery into furrows.

Eight- or ten-in. pipe diameters are usual. Where small streams are available, some 4- or 6-in. pipe is used. An irrigator

can handle 8- or 10-in. pipe in 10-ft. lengths. Larger pipe requires two irrigators. The size of pipe and usable velocities limit the heads handled to 1 or 2 sec.-ft. Canvas hose has also been used; the greater work of drying between irrigations and shorter life balance its lower first cost and it is now seldom used. The standard-weight galvanized surface pipe with slip-joint ends costs about 40 cts. for 8-in. and 50 cts. per foot for 10-in. pipe under usual conditions. For the smaller sizes 24- or 26-gage metal is used and 20- or 22-gage for the 8- or 10-in. sizes.

The irrigator can work away from the source of supply in applying water by this method. When the area at the end of the

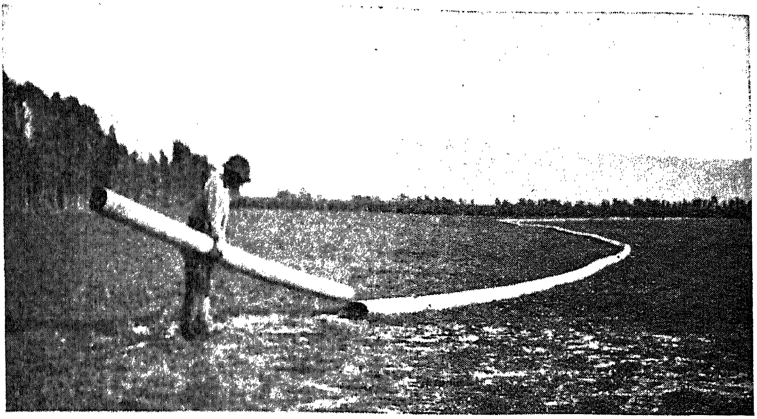


FIG. 59.—Surface-pipe method of irrigation. (*Courtesy of Division of Irrigation Investigations and Practice, California Agricultural Experiment Station.*)

field pipe has been covered, two to four additional lengths are connected and the next area flooded. The pipe is connected without stopping the flow. The pipe can be also connected across the field with irrigation toward the supply, disconnecting the pipe as each area is wet. The pipe is also disconnected without shutting off the flow. Formerly, galvanized iron elbows closed with wooden blocks were used to deliver water from the supply lines to the field lines, a piece of canvas being used as a flexible connection between the elbow and the first section of pipe. Present practice consists mainly of the use of portable hydrants (Fig. 60). These permit opening and closing the valves in the distributing stand while the field pipe is connected. Two portable hydrants may be used, the one in use not being closed until the other has been connected and started in use. Valves in the

distributing stands which permit larger flow are used for surface-pipe irrigation than those used for furrows. The usual costs for such valves are about $4 for 8-in. to $6 for 12-in. sizes. The portable hydrants cost about $20 to $25 for the 8- and 12-in. sizes, respectively.

The surface-pipe method is the most laborious of the flooding methods. The small heads used limit the area an irrigator can

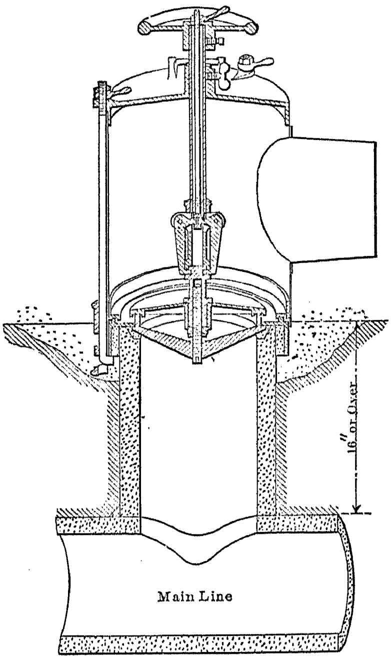


FIG. 60.—Cross section of stand pipe, alfalfa valve, and portable hydrant.

cover in a day. The handling of the pipe represents an added labor compared to other methods. Its use is limited mainly to locations of scarce or expensive water where the saving in percolation losses compared to the use of field ditches or in land leveling balances the added cost of application. It is often used on farms where the main area is furrow-irrigated from pipe lines and the surface pipe is used on the part of the area flooded.

FURROW METHOD

The furrow method of irrigation consists of the application of water in small ditches or furrows in which water is run so as to

secure sufficient moistening of the soil. It differs from the flooding methods in that water is applied to only a portion of the soil surface.

The furrow method is used in orchards, for crops grown in rows, and for forage and cereal crops where the soil or topography is not suited to flooding. With orchards, the tree spacing permits a relatively wide choice in the number and arrangement of the furrows used. For row crops, the row spacing determines the furrow spacing. For uniform distribution of water, the furrows must be spaced sufficiently close to give adequate lateral penetration in the depth of soil containing the roots of the crop; the length of the furrows must be adjusted so that excessive loss does not occur from deep percolation at the head of the furrows before adequate moisture has reached the lower end; and the flow in each furrow must be properly controlled and regulated to give the desired depth of irrigation.

Water is conveyed to the head of the furrows in ditches, flumes, or pipes. Usual lengths of furrows are 330 to 660 ft. On heavy soils some furrows may be as long as 1,320 ft. but it is difficult to regulate the flow in such furrows, and a length of 660 ft. is preferable even in soils which absorb water slowly. In coarse-textured soils, furrows as short as 150 ft. may be required if excess percolation at the upper end is to be prevented.

By limiting the size of stream used in each furrow, this method may be used on steep lands. Furrows are used on the steepest lands which are irrigated. While nearly all lands which it is desired to irrigate have slopes of less than 2 per cent, irrigation is practiced in some cases on slopes as steep as 10 or even 20 per cent. On steep lands, systems of zigzagging may be used or the grade of the furrows may be reduced by running diagonally to the slope of the land. However, it is generally preferable to run the furrows straight down the steepest slope and avoid erosion by the use of small streams. If furrows diagonal to the slope break over, the water follows the slope of the land to the next furrow below and the augmented flow will usually cause erosion. Furrows down the slope seldom break over and the water can be adjusted to follow the course of the furrow without injury. For usual conditions a grade in the furrows of 3 to 6 in. per 100 ft. is desirable. Flatter grades require short furrows to secure uniform distribution. While the furrow is equivalent to a small ditch the small size of the furrow results in much smaller velocities than in

usual sizes of farm ditches and requires steeper grades to obtain effective results.

The spacing of row crops varies. Sugar beets are planted with spacings from 18 to 24 in.; the rows in potatoes, corn, and cotton are more usually 3 to 3½ ft. apart. The narrow spacing of sugar beets limits the size of furrow which can be made without covering the plants. On land of uneven slope, a good deal of cross flooding frequently occurs in beets, giving a mixture of flooding and furrow practice. With potatoes the rowing out of the crop results in wide deep furrows in which larger areas of absorption can be secured. In orchards planted on the usual 20- to 24-ft. tree spacings, four furrows per tree row are typical of usual practice. With young trees one or two furrows close to the tree are usual; as the tree grows and extends its root system, the entire space between tree rows should be moistened. With mature trees it is difficult to get furrows within 3 or 4 ft. of the tree rows, which gives a spacing of 6 to 8 ft. across the tree row. It is difficult to secure lateral percolation across such spacing.

In order to secure better moisture distribution in the tree rows, various forms of cross furrowing are used. Typical cross-furrow practice is shown in Fig. 61. In Fig. 61 furrows are made in the direction of flatter slope in the orchard with cross furrows in the center of each tree row. Water is run in the center furrows and flows into the cross furrows where it stands until absorbed. On steep lands, dams may be needed along the center furrows to force water into the cross furrows. This in effect gives a corrugated basin with the advantages of more complete spread of the water without the disadvantages of complete wetting and baking of the surface soil. Cultivation can follow irrigation more quickly on cross-furrowed land than with basins.

FIG. 61.—Cross furrowing in orchard.

Where furrows are used for forage and grain crops, the practice is usually called the "corrugation method."[7] This practice is extensively used in the northwest on lands which may erode under flooding and which tend to bake. The corrugations avoid wetting the entire soil surface and can be handled on steep slopes

without erosion. The corrugation method is an adaptation of the furrow method to crops where the furrows cannot be cultivated after irrigation. The furrows in the corrugation method are relatively shallow. In alfalfa on sandy lands, cleaning of the furrows may be needed after each cutting; for other soils cleaning once per season is usual. The spacing of the corrugations varies from $1\frac{1}{2}$ to 3 ft. For new seeding, the corrugations may be spaced 18 in. with alternate furrows abandoned after the stand has become established. For usual conditions, spacing of 20 to 24 in. results in quicker cross percolation and more effective distribution than spacing of $2\frac{1}{2}$ to 3 ft.

Furrows are generally made by attachments on the equipment used in cultivation, the earth from the furrow being crowded to the sides. On steep slopes a rough furrow aids in retarding the flow. Where the slope is small or where a small furrow is used as in corrugation, it may be desirable to smooth the furrow to aid the flow, and furrowing sleds such as that shown in Fig. 62 are used.

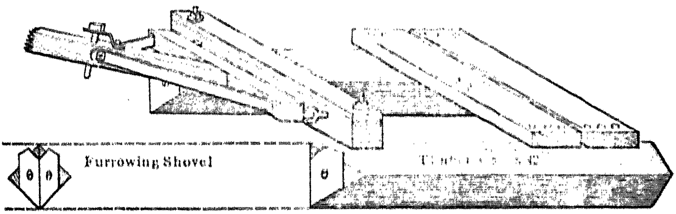


Fig. 62.—Furrowing sled. (*Roeding.*[12])

The total size of stream handled by an irrigator in the furrow method varies from a part of a second-foot to 2 or 3 sec.-ft. For steep areas the heads vary from a few miner's inches as in the foothill fruit areas of California to $\frac{1}{4}$ to $\frac{1}{2}$ sec.-ft. Head of $\frac{3}{4}$ to $1\frac{1}{2}$ sec.-ft. are representative of usual practice.

The stream used in each furrow also varies. For the relatively large furrows of such crops as potatoes, 0.06 to 0.08 sec.-ft. per furrow may be used. For usual conditions the flow per furrow does not exceed 1 miner's inch or 0.02 sec.-ft. per furrow. On heavy soils or steep slopes the flow per furrow may be only $\frac{1}{200}$ sec.-ft., or $\frac{1}{4}$ miner's inch. The area supplied per furrow, the stream used, and the time of delivery are adjusted to give the depth of irrigation desired. The stream used per furrow is limited by the amount of absorption that will occur from the furrow. While the initial absorption that occurs as the water works

through the furrow may result in slow progress, after water has reached the lower end the rate of absorption may be so small that long times of set are required to secure adequate depth of absorption. On very heavy soils, in some cases, sets as long as 3 or 4 days are used. Much orchard practice uses sets of 24 hr.; 6 to 12 hr. are representative of the shorter periods for soils that take water readily.

A furrow serving an area 6 ft. wide and 660 ft. long receiving a flow of 1 miner's inch or 0.02 sec.-ft. will receive an average depth of irrigation of 1 in. for each 4½-hr. water runs in the furrow. On medium soils such a flow would be absorbed in such a furrow and a 24-hr. set would give a desirable depth of irrigation. A larger flow until water has reached the lower end, which is then reduced to the amount of absorption, will improve the uniformity of distribution. For heavier soils, smaller flows and longer times would be used. For smaller spacing or lengths, smaller streams or shorter times should be used.

DISTRIBUTION OF WATER TO FURROWS

The field-distribution system for furrows is adjusted to the topography. For regular slopes a rectangular system of distribution can be used with the field lines spaced in accordance with the length of furrow used. For irregular slopes the distribution system is located so as to cover the ridges with the furrows running from the controlling elevations.

The distribution system may consist of earth ditches, flumes, or pipe. Different methods of dividing the water into each furrow may also be used. Each of these methods has its field of usefulness.

Earth Ditches.—Water may be delivered to furrows from earth ditches through shovel cuts in the bank. The flow in the ditch is checked with dams similar to those used in wild flooding. This method has a low first cost but requires more care and attention during the irrigation, with a consequent increased labor cost. It is also difficult to secure a uniform distribution between furrows. This method is frequently used where land usually irrigated by flooding is planted in row crops for 1 to 3 years in the crop rotation. For such conditions the cost of the more accurate methods of division may not be justified for the short period of use.

The water may be delivered directly from the supply ditch to each furrow or to a group of furrows. The latter method per-

mits a secondary regulation and reduces the opportunity for excess diversion to any group of furrows by erosion of the opening.

An improvement over the open-cut turnouts for delivery from earth ditches consists of the use of tubes set in the ditch bank (Fig. 63). With tubes of equal size set the same distance below the water surface, relatively uniform flow into each furrow is obtained. The tubes may consist of square openings made of lath or various forms of pipe. The lath tubes are usually made of four pieces $1\frac{1}{2}$ by $\frac{1}{2}$ in., giving an effective opening of about 1 sq. in. and a discharge of about 1 miner's inch per tube. A length of $2\frac{1}{2}$ to 3 ft. is sufficient to extend through the bank of the small ditches used. Galvanized pipe is also used for this purpose. Such tubes are frequently used with the corrugation method or for rotated crops where furrows are used for periods equivalent to the useful life of the tubes.

FIG. 63.—Lath tubes delivering water to furrows from earth ditch.

Flumes.—Wooden head flumes set on the ground or supported across depressions may be used. These consist of three boards of

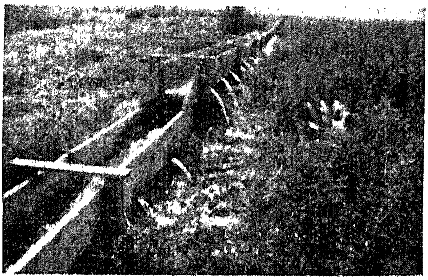


FIG. 64.—Use of small wooden flumes for delivery of water to furrows in the irrigation of alfalfa by the corrugation method in Washington.

1 by 12 in. or 1 by 8 in., with holes bored in the sides fitted with light galvanized iron slide gates (Fig. 64). On rough lands where small heads are handled, two boards may be used forming a triangular flume. Such flumes have been extensively used in the northwest. The useful life varies from 5 to 8 years under usual

conditions of operation. Where lumber costs are low, this represents an economical practice.

Concrete flumes have been used in much of the early California citrus practice. Delivery from the flume is made through galvanized spouts or tubes ¾ to 1½ in. in diameter inserted in the side of the flume before the concrete hardens. Checks may be placed across the flume to give more uniform flow to each furrow (Fig. 65). The usual sizes vary from 8 by 11 to 12 by 24 in. costing 20 to 30 cts. per lineal foot. Such flumes represent desirable practice where water is valuable and furrows are to be used permanently as in orchards. While much concrete flume is still in use, very little new flume is now being installed, concrete pipe having replaced the flumes for conditions where concrete is used.

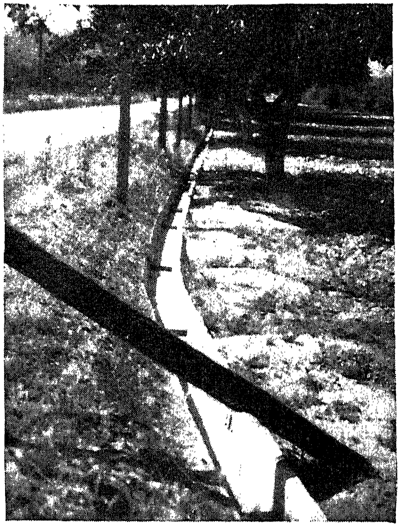


FIG. 65.—Concrete flume for delivery of water to furrows.

Concrete Pipe.—Concrete pipe is extensively used for delivery to furrows where permanent construction is desired. Such pipe systems have the advantage over flumes that, since they are buried, no land is lost from cultivation and use along the pipe lines. Less handwork is required in completing the furrows for the stands used with such pipe than with flumes. A typical arrangement of a concrete-pipe system is shown in Fig. 66. Such a system includes the same elements of supply and distribution lines and structures as for open-channel systems. The pipes are buried so as to have an earth covering of at least 1 ft. over the top of the pipe. In areas subject to freezing, greater cover should be used.

At the head of each tree row and in line with the trees, a distributing stand is connected to the supply line (Fig. 67). In walnut orchards where the trees are spaced 40 to 60 ft. apart, an intermediate stand is often used. Supply lines are required at spac-

ings equal to the length of furrows. Drainage valves should be placed in depressions and at the end of lines, so that silt or trash may be flushed out or the pipe drained to prevent freezing in areas of low winter temperature.

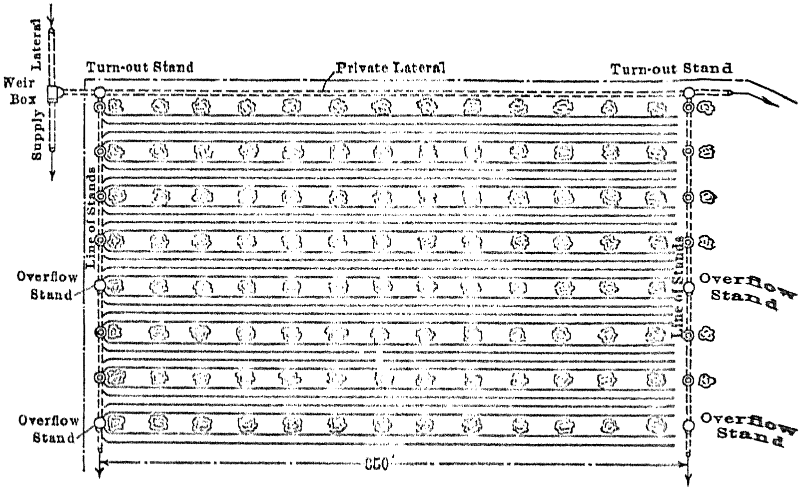


FIG. 66.—Concrete-pipe system of distribution for furrow irrigation of an orchard.

In Figs. 68 and 69 are shown different arrangements of distributing and control stands used in concrete-pipe systems. Figure 68 includes a general diagram of a pipe-line system and stands. Water is received from the source of supply under sufficient pressure to rise for distribution in the highest distributing stand. At intervals along the pipe line, control stands are used to regulate the pressure in the supply line. These may have a slide gate on the outlet side of the control stand or a pressure gate on the inlet side, as shown in the two illustrations in Fig. 69. The stands with the gate on the outlet side have to extend above the pressure level of the water in the supply line. For the quality of pipe formerly used in many systems, such pressures should not

FIG. 67.—Distribution stands on concrete-pipe system set in line of tree rows.

exceed 15 ft. For the character of pipe now more generally used the pipe can withstand larger pressures. However, for convenience in handling the gates, such stands are usually inserted in the

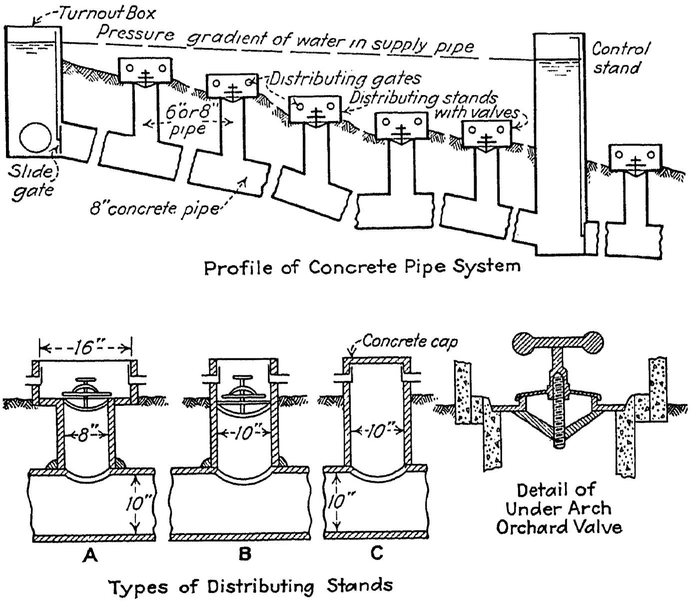


FIG. 68.—Details of concrete-pipe systems.

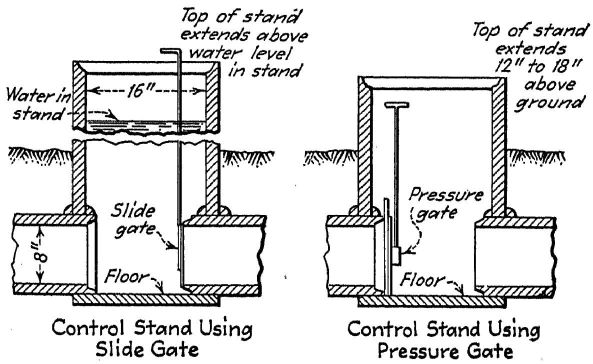


FIG. 69.—Typical stands used to control flow in concrete-pipe systems.

supply lines at differences of elevation of not over 6 to 8 ft. and on flat lands may be placed at smaller differences to avoid too great distances between points of regulation. The pressure gates are

equipped with gears or wedges to hold the gate in place against the upstream water pressure. Such gates do not give any relief to the pressures that may be caused by closing the gate quickly. For such relief a vent pipe may be attached to the supply line above the gate.

Several varieties of distributing stands are used. Three types are shown in Fig. 68. Type A consists of a riser pipe attached to the supply line and extending to the ground level. Surrounding the riser pipe is an enlarged basin with the distributing gates

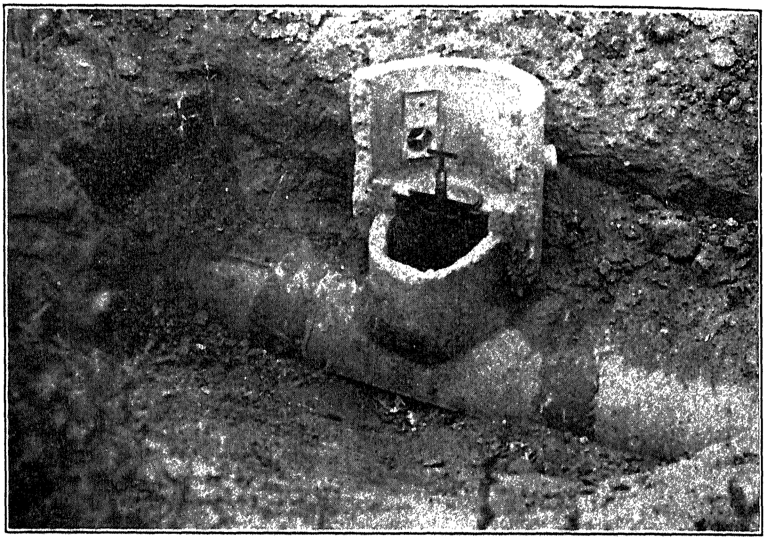


FIG. 70.—Distributing stand for delivery to furrows from concrete-pipe system showing method of construction.

serving the individual furrows. The riser pipe is saddled over an opening in the supply line. A valve set in the top of the riser pipe regulates the flow entering each distributing stand. Figure 70 is a picture of such a stand, cut away to show its construction. The riser may be 6- or 8-in. pipe, the basin may be 14 or 16 in. in diameter.

Type B stand consists of a single size of riser pipe in which the valve is inserted and from which the distributing gates deliver to each furrow. While this type is simpler to construct than Type A, it has the disadvantage of giving less distance between the

distributing gates, with increased difficulty in keeping the flow to each furrow separate. It is also more difficult to saddle the riser pipe on to the supply line when the diameter of the riser pipe is equal to that of the supply line. Instead of a separate distributing gate for each furrow, much practice now attaches metal pipe with gates for each furrow to a larger distributing gate in the stand as shown in Fig. 71. Such pipes are removed between irrigations. This method eliminates the handwork of connecting the furrows with the stand.

Type C represents a capped stand in which a concrete cap closes the top of the riser pipe. This avoids the use of the valve

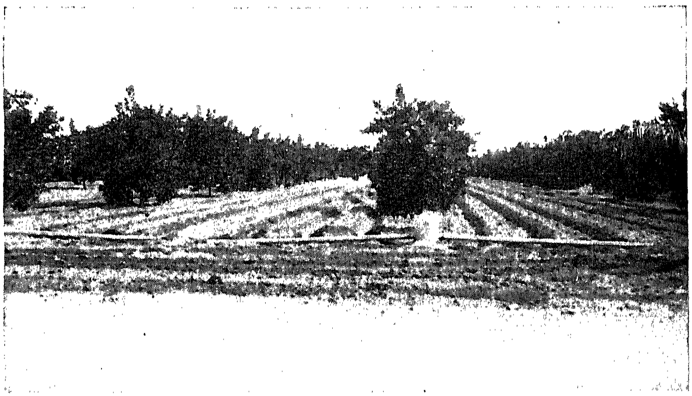


FIG. 71.—Concrete-pipe system for furrows in orchard with removable metal pipes having gates for each furrow. (*Courtesy of Division of Irrigation Investigations and Practice, California Agricultural Experiment Station.*)

in the stand but subjects the stand to the full water pressure of the supply line. In this stand the distributing gates need to be of heavier construction. The gates are placed on the outside of the stand. For Types A and B the distributing gates are usually placed on the inside of the stand where they are not liable to injury by the implements used in cultivation.

Many other varieties of distributing stands are used.[8] On land of small and even slope, open stands without valves can be used if control stands are placed at 12- to 18-in. difference in elevation to control the pressure so that the distributing stands will not overflow. Such overflow systems were formerly more generally used than at present, as the certainty of control with the valve

justifies the added cost. Distributing stands having a basin made of one-half of a 30-in. pipe or an oval basin of similar size may be used where more than four distributing gates are desired. On steep side hills each distributing stand may be combined with an overflow so that excessive pressure cannot accumulate in the supply line.

A detail of one type of valve is also shown in Fig. 68. Such valves may be supported from below the valve seat as shown, or an overarch may be used. Some valves are made so that the support and valve may both be removed when unobstructed flow is desired. This type is more generally used in flooding from pipe lines than for furrow practice.

General costs for the accessories used with concrete-pipe systems for delivery to furrows are shown in the following tables. Costs of concrete pipe are discussed in Chap. VII. The galvanized-iron distributing gates are used for delivery from the stands to the furrows. The smallest sizes are used for delivery to single furrows; the larger sizes are used where pipes are attached to the outlet of the gate for delivery to more than one furrow. The valves are those used in the distributing stands to control the flow into the stand from the supply line. The underarch valves have the valve-stem support beneath the valve opening as in Fig. 68. The high-seat valve has the valve stem supported above and outside the valve opening. The slide gates are those for use in control stands where the pressure of the water tends to hold the gate against its seat. They are of light construction and are not watertight under pressures from the opposite direction. The pressure gates have screw or gear arrangements for wedging the gate against its seat so that the gate is tight against pressure tending to push it away from its seat. The distributing stands refer to the types as designated in Fig. 68.

Cost of Galvanized-iron Distributing Gates

Diameter of Opening, Inches	Cost per Gate
1	$0.08
1½	0.10
2	0.11
3	0.35
4	0.45

Cost of Valves

Number of valve	Size of opening	Cost per valve	
		Underarch type	High-seat type
6	3½	$0.75	$1.15
8	5	0.90	1.40
10	6½	1.50	2.00
12	8	2.50	3.00
14	10	4.00	4.25

Cost of Gates

Size of opening, inches	Cast-iron slide gates	Cast-iron pressure gates
6	$2.35	$ 6.00
8	2.90	8.00
10	4.30	11.00
12	5.50	15.00
14	6.60	21.00
16	9.00	26.00

Cost of Distributing Stands Complete

Type	Cost
A	$3.50
B	3.00
C	2.00

Pipe Other than Concrete.—Wood, vitrified-clay, or steel pipe may be used for delivery to furrows. Vitrified-clay pipe is more brittle than concrete and, as it is usually more expensive than concrete pipe, it is used to only a limited extent in irrigation. Such clay pipe will not stand large pressures; it is, however, resistant to alkali. The larger cost of steel pipe and of the connection of stands limits its use for delivery to furrows. In a few areas where irrigation water is delivered under pressure, steel pipe with faucets at each tree row is used. The water delivered by each faucet may be discharged into a concrete basin similar to the upper portion of Type A (Fig. 68) for distribution to furrows. Surface slip-joint pipe may also be used with furrow

slide gates as in Fig. 72. Such furrow gates attached to steel pipe cost 25 to 30 cts. each for the 1- to 2-in. sizes.

Machine-banded wood stave pipe is used in some areas of steep or rough land where pressures may exceed those for which ordinary concrete pipe is suited. Wood pipe may be tapped for deliveries to furrows by screwing in ordinary garden faucets or by the use of wooden plugs as in Fig. 73. The wood pipe may be either buried or laid aboveground. Its higher first cost and

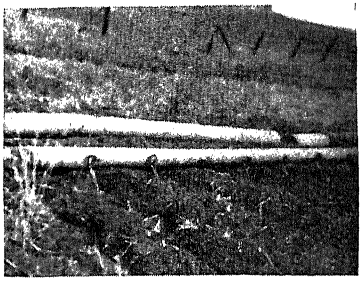


FIG. 72.—Steel surface pipe with side gates for delivery to furrows.

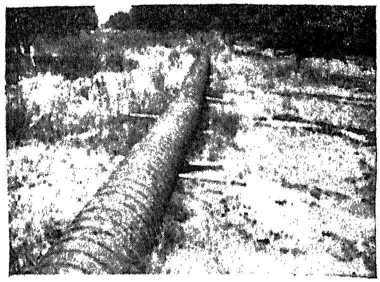


FIG. 73.—Delivery to furrows from wood stave pipe.

generally shorter life make the use of concrete usually preferable for conditions to which both types of pipe are adapted.

CONTOUR FURROWS

For steep lands planted in orchards, a practice known as "contour furrowing" has been developed. This is a combination of contour checks and furrows. The land is prepared in strips of the width of one tree row located nearly parallel to the contours but with enough slope to provide grade for the furrows. Furrows are used to irrigate these strips. This method reduces the cost of leveling, permits the application of water with less risk of cross washing than for similar furrows without contouring, and avoids deep cuts on shallow soils. It has been used for many new plantings of orchards in California (Fig. 74). It is not applicable to old orchards, as the regularity of planting affects the grading. The trees may be uniformly spaced along a grade contour to give irregular cross rows; they may be spaced irregularly on a uniform grade contour to give straight cross rows, or the grades of the contours may be varied to give straight cross rows.[9] Where the slope varies, it may be necessary to pinch out or add a tree row.

Both flumes and pipe distribution systems are used. Field lines run down the steepest slopes. Frequent control stands are required for pipe distribution and in some practice each stand is

FIG. 74.—Orchard planted on contour furrows in California. (*Courtesy of Division of Irrigation Investigations and Practice, California Agricultural Experiment Station.*)

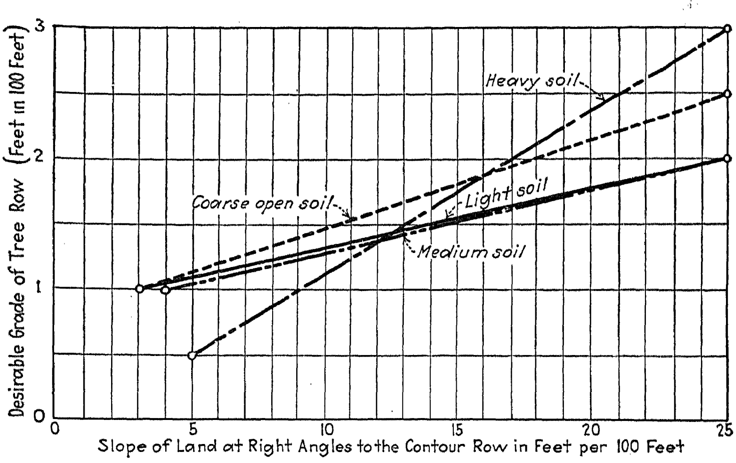


FIG. 75.—Desirable grades for contour planting of orchards. (*Huberty and Brown.*[9])

made to act as an overflow stand so that excess pressure cannot accumulate in the line. Four furrows per tree row are frequently used; in some cases for shallow soils over impervious subsoils one furrow on the uphill side is used to sub-irrigate the contour.

On very steep land the trees may be set in pockets or small basins filled from a single furrow on the uphill side.

In order to get water through the furrows without too much seepage down the slope, fairly steep grades are used. The grades vary with the soil. Desirable grades are indicated by Fig. 75.[9] For usual conditions, grades of 1 to 2 per cent should be used. Furrow lengths vary from 300 to 600 ft.

SPRINKLING METHODS

Various methods of sprinkling have long been in use for lawns and gardens. Some applications of sprinkling to crops have been

FIG. 76.—Rotary sprinkling method of irrigation in a California orchard. (*Wadsworth.*[10])

made. The necessarily high cost of most of these methods limits their application to conditions of scarcity and high cost of water and high value of crops. Such conditions occur in some portions of southern California and many sprinkling installations have been made there. Some supplemental irrigation is also practiced in humid areas in the eastern United States. Smaller depths of irrigation can be more uniformly distributed with the sprinkling method than with other methods. Surface waste and deep-percolation losses can be prevented. Evaporation losses may be relatively large under arid conditions.

Various arrangements of sprinklers are used.[10] The installations may be movable or permanent. For permanently placed systems the sprinklers are placed above the tops of the plants and

also high enough to permit operation of farm equipment. For orchards, sprinklers are placed above the trees. In several systems of sprinkling, vertical pipes with revolving circular sprinkler heads are used, either permanently connected to buried supply pipe lines or movable with hose connections to the supply (Fig. 76). Sprinkling may also be accomplished from parallel lines of pipes with perforations a few inches apart to give the required spray. Such pipe may be rotated so that a single row of perforations may serve a wider area on both sides of the pipe line by changing the position of the openings. For some truck practice, perforated pipes rolled along supports have been used.

Sprinkler systems of the above types cost from $150 to $200 per acre to install. For operation, including friction losses and the pressure required at the nozzles, a total pressure equivalent to a lift of about 100 ft. above the ground level is required. The resulting total costs limit the use of such sprinkling to citrus fruits, nursery stock, or similar intensive practices with large returns. While many individual installations have been made, the total area served by this method in the localities in which it is used represents only a small proportion of the total area irrigated for similar crops by other methods.

In some cases, portable pumps are used for sprinkling, the water supply being obtained from shallow ground water or conveyance channels in the area served. Movable lines of pipe with risers carrying sprinkler heads are supplied by the portable engine and pump. Such systems have lower costs of installations. Similar amounts of pumping lift are required to furnish pressure for the operation of these systems as for the other types.

SUB-IRRIGATION

Sub-irrigation is either the control of the water table on lands having a high water table or the supplying of soil moisture by underground conduits which, except for soil underlaid by impervious subsoils, need to be spaced as closely as furrows in furrow irrigation. As such methods avoid surface evaporation, soil baking, and surface distribution systems, many efforts have been made to serve lands by sub-irrigation.

Natural sub-irrigation is used in some areas of porous subsoil with the water table controlled so that moisture reaches the plant roots by saturation or capillary rise from below. This condition occurs in portions of the peat lands of the Sacramento River

delta. On the peat soils in which lateral penetration is rapid, water is held to the height desired in ditches 50 to 100 ft. apart (Fig. 77). The water moves through the peat to meet across the areas between the ditches. The water in the ditches is then lowered and the soil drains, leaving moisture within reach of the crops. Similar sub-irrigation is practiced in some sandy lands. Except on peat soils, it is difficult to control such sub-irrigation, and waterlogging usually results on at least part of the area. This method also results in alkali accumulation at the surface if alkali is present in the soil.

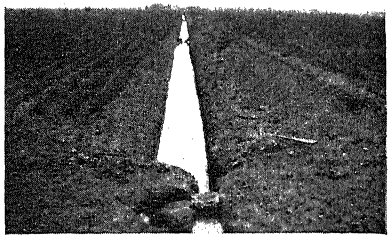


FIG. 77.—Field ditch used in sub-irrigation of peat lands in Sacramento River delta, California.

Artificial sub-irrigation by seepage from underground channels or conduits has been tried. This is equivalent to a reversal of the usual process of drainage. Such methods have been used for lawns but have not been successful for commercial crops or deep-rooted plants. The conduits need to be spaced 4 to 6 ft. apart in order to secure adequate lateral spread of moisture. Such spacing results in costs in excess of the benefits for commercial crops. Plant roots seek the outlets from the conduits, and uniformity of moisture distribution has not been successfully maintained.

References

1. DEAN, H. K.: The Management of Sandy Soils under Irrigation, *Oregon Agr. Exp. Sta. Bull.* 177, 1921.
2. BOYD, G. R.: Clearing Land of Brush and Stumps, *U. S. Dept. Agr. Farmers Bull.* 1526, 1929.
3. SCUDDER, H. D.: Stump Land Reclamation in Oregon, *Oregon Agr. Exp. Sta. Bull.* 195, 1922.
4. BONEBRIGHT, H. B.: Irrigation Practice in Montana, *Montana Agr. Exp. Sta. Circ.* 29, 1913.

5. FORTIER, S.: The Border Method of Irrigation, *U. S. Dept. Agr. Farmers Bull.* 1243, 1927.
6. BROWN, J. B.: The Irrigation of Alfalfa, Border or Strip Check Method, *California Agr. Ext. Service*, 1931.
7. MARR, JAMES C.: The Corrugation Method of Irrigation, *U. S. Dept. Agr. Farmers Bull.* 1348, 1923.
8. STANLEY, F. W.: The Use of Concrete Pipe in Irrigation, *U. S. Dept. Agr. Bull.* 906, 1921.
9. HUBERTY, M. R., and J. B. BROWN: The Irrigation of Orchards by Contour Furrows, *California Agr. Ext. Service Circ.* 16, 1928.
10. WADSWORTH, H. A.: Irrigation by Overhead Sprinkling, *California Agr. Ext. Service Circ.* 4, 1926.
11. FORTIER, S., and M. R. LEWIS: Practical Information for Beginners in Irrigation, *U. S. Dept. Agr. Farmers Bull.* 864, 1932.
12. ROEDING, F. W.: Irrigation of Sugar Beets, *U. S. Dept. Agr. Farmers Bull.* 392, 1910.

CHAPTER VII

FARM DISTRIBUTION SYSTEMS

The water supply for an irrigated farm is obtained usually from one of the laterals of the irrigation system, which serves a number of farms or a large area of land. It may also be obtained from a pumping plant and in some cases directly from a natural water course. When the water supply is obtained from a lateral of an irrigation system, the water is delivered to the farm through a delivery gate, which may also serve as a measuring gate or which may be combined with a separate measuring device. When the water supply is developed by pumping, the water may be either delivered in a receiving box, which may be a measuring box, or in a farm reservoir, or discharged directly into the main ditch or conduit of the distribution system.

The delivery gates and measuring devices are usually constructed by the main canal organization and are a part of the main canal system. Their design and construction are discussed in Vol. III of this series. Methods of measurement are also discussed in Vol. III.

The distribution system of an irrigated farm includes the system of ditches or conduits required to convey the water from the point of delivery to the different parts of the farm, and of the farm structures required to regulate, divide, and distribute the water to the land. The character of the distribution system will depend largely on the area of the farm, the topography, the method of irrigation, and the value of the water. For large farms having an area of several hundred acres, the distribution system may include a number of laterals and structures similar in design to those forming part of a general irrigation system. The topography of the land will control to a considerable extent the method of irrigation, which is an important factor in determing the location and the capacity of the distribution system. The value of the water will determine the economy with which water should be used and is a factor in selecting the type of construction.

The farm ditches and conduits may be divided into those from which water is taken out and applied to the land, which are commonly called "field" or "distributing" ditches, flumes, or pipe lines, and those ditches or conduits which convey the water from the point of delivery to the field ditches, which may be called "supply" ditches, flumes, or pipe lines. The field ditches may be temporary earth ditches, which are made before each irrigation or before each season, such as for the wild-flooding method of irrigation for cereals and for some furrow-irrigation practice, or they may be permanent earth ditches with permanent structures, such as for the border or other check methods of flood irrigation which require ditches of larger capacity. For the furrow method of irrigation, flumes of wood or concrete or pipe lines with distributing stands may be used; these have been previously discussed in Chap. VI under the furrow method of irrigation. The supply conduits are usually more permanent than the field distribution system; they may be earth ditches, flumes of wood or concrete, or pipe lines.

The structures used on the farm distribution system consist of the structures used to regulate the flow in the supply and field ditches, such as check gates, division gates, drops, and the structures to take out and distribute the water from the head ditches or conduits, such as levee gates in the banks of field ditches to deliver water into checks. On the larger ditches, farm bridges may be necessary.

PLANNING AND LOCATION OF DISTRIBUTION SYSTEM

The planning of the distribution system requires a careful study of the topographic conditions, the crops to be grown, and the available head or stream of water, in order to determine the best method of irrigation. The distribution system is planned to fit the method of irrigation. For the wild-flooding method, the topography of the land to be flooded determines the position of the field ditches. For the check methods of flooding, the direction, length, and width of the checks determine the arrangement of the field ditches. The location of the field ditches controls the location of the supply ditches.

Where the land for the whole farm has a continuous slope in one direction without ridges or depressions, the supply ditch will usually be along one of the boundaries of the farm with the field ditches running at right angles to the supply ditch. Where the

land consists of ridges and depressions, the field ditches will be on the ridges with the supply conduits carrying the water across the depressions, using earth ditches in fill, flumes on supports above the ground, or pipe lines.

REQUIRED CAPACITY OF FARM DISTRIBUTION SYSTEM

The capacity of the distribution system for any farm is determined by the size of the irrigating head, which in turn depends on the method of irrigation. The most economical size of head is usually the largest amount of water an irrigator can handle without loss by surface waste. The minimum head is the smallest stream that can be used effectively without excessive deep-percolation loss. For wild-flooding and check methods a minimum head of 1 sec.-ft. is needed to enable economical use of water to be obtained; such heads, however, require preparation of the land in smaller areas and more labor cost in application. Small streams can be used with equal effectiveness with the furrow method by adjusting the number of furrows run at any time to the supply available; however, costs of application are increased where the number of furrows is less than that which the irrigator can attend effectively. In the wild-flooding method the maximum size of head an irrigator can handle effectively is about 3 to 4 sec.-ft. In the border and check methods as used in the San Joaquin Valley of California, heads of 15 to 20 sec.-ft. are delivered to individual farms. With furrow methods the head which one irrigator can handle is seldom larger than 1 to 1½ sec.-ft. The total head received by the farm determines the capacity of the supply ditches; the supply may be divided among more than one field ditch, thus reducing their capacity.

DESIGN AND CONSTRUCTION OF FARM CONVEYANCE CHANNELS

The design of a channel to obtain the determined capacity depends on a number of factors, the most important of which are the grade of the ditch, the velocity, the form or shape of the ditch cross section, and the method of construction. These factors, as well as others, are considered in detail, especially from the standpoint of the engineer, in Vol. II. It is, however, desirable to present briefly in this chapter some of the principles of flow of water.

The flow of water is governed by the following laws:

1. The area of the water cross section in square feet multiplied by the velocity in feet per second gives the discharge in cubic feet per second.

2. The velocity of flow increases with the grade. When all other conditions, including the area of the water cross section, remain the same, the velocity and therefore the carrying capacity increases very nearly with the square root of the grade; for example, if the grade is multiplied by 4, the velocity and carrying capacity are practically doubled.

3. The velocity increases with an increase in the degree of smoothness of the sides and bottom of the channel in contact with the water; as an example, when all other conditions are the same, the velocity and capacity of a rough earth ditch will be only about half of that of a very smooth concrete-lined ditch.

4. The velocity is affected to some extent by the form of the cross section of the channel. For a given cross-sectional area, the form of section having the least wetted surface in contact with the water will have the highest velocity. For a given area, the form which will have the smallest wetted area is a semicircle. For earth ditches, a semihexagon form has nearly as large a ratio of cross section to perimeter. In practice, however, the farm ditches are usually made comparatively shallow and broad; this form is more easily constructed and, as ordinarily built by using the excavation to make the banks, will carry a larger part of the water above the original ground surface.

5. In a given channel the velocity increases with an increase in the volume of water in the channel. For instance, a flume 3 ft. wide carrying water to a depth of 1 ft. with an average velocity of 3 ft. per second gives a discharge of 9 sec.-ft. When it carries a depth of 2 ft., the area of the cross section is doubled and the velocity is increased to about 3.87 ft. per second, giving a discharge of 23.2 sec.-ft., or 2.58 times as much as for the smaller depth.

FARM DITCHES

Farm ditches are not usually excavated and trimmed to trapezoidal sections as are the larger canals and laterals of an irrigation system. The form of farm ditches depends largely on the method of construction, which varies with the size of the ditch A farm ditch is usually built partly in cut and partly in fill.

When the volume of cut from the ditch equals the volume of material in the banks, it is called a "balanced cut-and-fill ditch." Such a ditch is the cheapest type of construction, as it involves the minimum amount of earthwork, but is not always feasible or desirable. A balanced cut-and-fill section will usually hold the water level in the ditch somewhat above the ground level. Where water is to be delivered on to adjacent land, it is necessary to have the water in the ditch a minimum of 4 to 6 in. above the elevation of the adjacent ground to supply depth of flow on the land and loss of head in the turnout. This will usually require

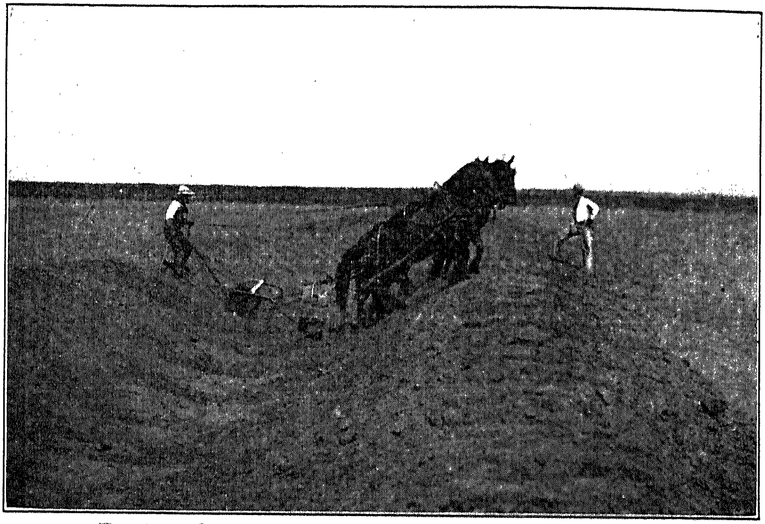


FIG. 78.—Constructing a farm ditch with a Fresno scraper.

building up the ditch banks higher than will be obtained by balancing the cut and fill. The banks are raised with earth from outside the ditch. It is not necessary to hold water so much above the ground in ditches used for conveyance without delivery on adjacent land, and for such supply ditches a balanced cut-and-fill section may be used. When a ridge must be cut through, the water may be entirely below the ground; when a depression is crossed in fill, the entire ditch may be above ground.

The larger farm ditches, having a bottom width of about 3 ft. or more, are usually constructed with Fresno scrapers (Fig. 78) worked back and forth across the ditch, removing the material from the cut into the banks. Except for loose or sandy soils,

plowing of the cut may be required. The tramping of the teams compacts the banks. The resulting ditch has side slopes of about $1\frac{1}{2}$:1 to 2:1, with the bottom of the ditch and the crown of the bank rounded. The larger ditches may also be constructed with a road grader, which for such use requires adjustments permitting the blade to be set at the desired side slope. The material is loosened by plowing; the scraping out leaves smooth side slopes, but the banks are not compacted and are liable to break if water is held above the ground surface before the banks have settled. Both manufactured and homemade ditchers, while frequently

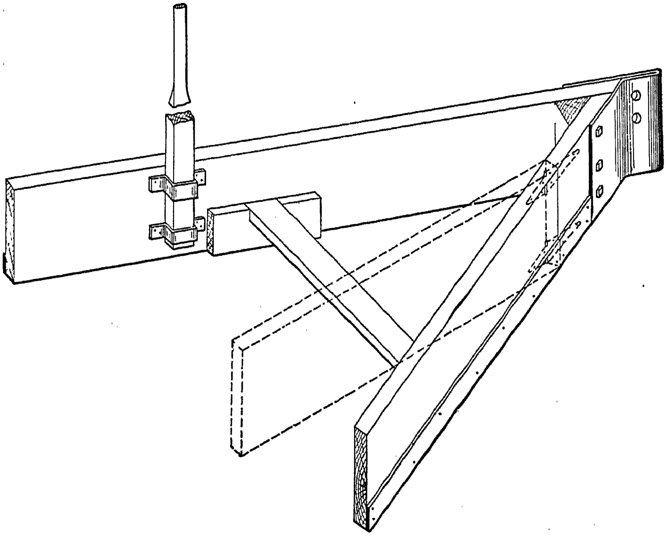


FIG. 79.—Wooden V-crowder for making small earth ditches.

used for small ditches, are not generally used for the larger sizes of farm ditches.

Smaller ditches may be built by plowing, using an ordinary lister, a double moldboard ditch plow or a homemade ditcher formed of right and left plowshares placed side by side and spread so as to make a ditch about 18 in. to 2 ft. on the bottom. Such ditch plows should have long moldboards to turn the earth well out of the ditch into the banks. Another device very commonly used for small ditches is the V-crowder. This is dragged up and down the ditch, crowding the earth into the banks. Plowing the alignment of the ditch is needed before using the crowder unless the

soil has been recently loosened. The crowder leaves narrow loose banks, easily broken through when the water is raised against them unless they have time to settle before used. The V-crowder may be built of wood (Fig. 79) or of steel (Fig. 80). They are frequently made adjustable to the size of ditch by use of a hinge joint in one side near the point of the V and a variable spacer near the rear end as in Fig. 79.

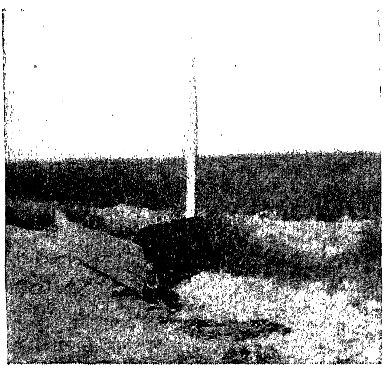


FIG. 80.—Steel ditcher used in making farm ditches.

Cross sections of typical farm ditches are shown in Fig. 81. These cover the range of sizes needed for such ditches. Even with small irrigation heads, ditches smaller than Form 1 are rarely used. Form 6 is as large as would be required for farm conditions. Rounded sides slopes of about $1\frac{1}{2}:1$ are representative of average practice. The top widths of bank shown represent good practice, although many ditches are built with less liberal dimensions. The freeboard, or the height of bank above the depth of water, shown is also larger than that allowed on many ditches. It is good practice to use ditches with adequate banks, so that the attention of the irrigator can be given to the irrigation rather than to repair of ditch breaks. The water in these ditches, as shown, is not high enough to permit delivery on adjacent ground, but the freeboard is sufficient to enable the depth of water to be increased by checks during such deliveries.

For all except Form 6, the material in the banks of these ditches exceeds the excavation, so that additional earth would be required for their construction. For Form 6 the cut and fill balance. For supply or other ditches to be used continuously, such banking up is advisable. For temporary field ditches in wild flooding it is not usual to borrow earth for the banks, steeper and narrower banks being used.

Table XXIV gives the carrying capacities for various depths of flow and grades for the ditches shown in Fig. 81. The capacity of an earth ditch varies with its condition. The results shown in Table XXIV represent carrying capacities for ditches in average good condition (Kutter's n = 0.025). If allowed to become

silted or weed grown, the capacity will be reduced materially below the figures shown in Table XXIV.

The results in Table XXIV illustrate the principles of flow previously stated. The carrying capacity is usually known, as it is determined by the size of head available; the grade is usually

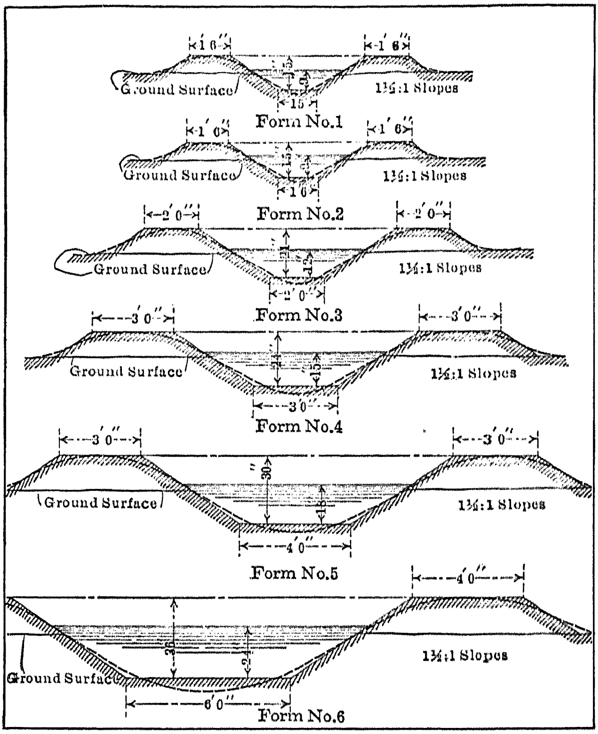


Fig. 81.—Sections of typical farm ditches.

determined by the location of the ditches in the distribution plan. Different sizes of ditches will meet given conditions of capacity and grade, depending on the ratio of bottom width and depth used. If the grade is such that the resulting velocity exceeds that which the soil can withstand, it is necessary to take up the excess grade by the use of drops or check gates at intervals along the ditch. When the conditions permit a variation in the position of the ditch line, a velocity may be selected and the corresponding grade obtained from the table. The maximum velocity that may be used depends on the resistance against scouring or erosion offered by the soil. Safe maximum velocities vary from 1 ft. per

TABLE XXIV.—CARRYING CAPACITIES OF FARM DITCHES

Form 1. Bottom width 1.25 ft., side slopes 1½:1

Grade, feet per thousand	Mean velocity, feet per second, for depths of			Carrying capacity, second-feet, for depths of		
	3 in.	6 in.	9 in.	3 in.	6 in.	9 in.
1	0.46	0.72	0.93	0.19	0.72	1.66
2	0.65	1.02	1.33	0.26	1.02	2.37
4	0.93	1.45	1.89	0.38	1.45	3.36
5	1.04	1.62	2.10	0.42	1.62	3.74
6	1.13	1.78	2.31	0.46	1.78	4.11
8	1.32	2.05	2.67	0.54	2.05	4.75
10	1.47	2.29	2.98	0.60	2.29	5.30

Form 2. Bottom width 1.50 ft., side slopes 1½:1

Grade, feet per thousand	Mean velocity, feet per second, for depths of			Carrying capacity, second-feet, for depths of		
	3 in.	6 in.	9 in.	3 in.	6 in.	9 in.
1	0.47	0.80	0.97	0.22	0.96	1.91
2	0.67	1.13	1.37	0.32	1.36	2.72
4	0.95	1.60	1.95	0.45	1.92	3.84
5	1.06	1.79	2.18	0.50	2.15	4.28
6	1.17	1.96	2.39	0.55	2.35	4.70
8	1.35	2.27	2.75	0.63	2.72	5.41
10	1.50	2.53	3.07	0.70	3.03	6.05

Form 3. Bottom width 2 ft., side slopes 1½:1

Grade, feet per thousand	Mean velocity, feet per second, for depths of			Carrying capacity, second-feet, for depths of		
	6 in.	9 in.	12 in.	6 in.	9 in.	12 in.
0.5	0.58	0.71	0.85	0.84	1.66	2.98
1	0.82	1.00	1.20	1.19	2.35	4.20
2	1.16	1.42	1.70	1.69	3.32	5.94
4	1.65	2.01	2.41	2.39	4.71	8.43
6	2.03	2.48	2.94	2.94	5.80	10.30
8	2.33	2.84	3.40	3.38	6.65	11.90
10	2.60	3.18	3.80	3.77	7.44	13.30

TABLE XXIV.—CARRYING CAPACITIES OF FARM DITCHES.—(*Continued*)

Form 4. Bottom width 3 ft., side slopes $1\frac{1}{2}$:1

Grade, feet per thousand	Mean velocity, feet per second, for depths of			Carrying capacity, second-feet, for depths of		
	9 in.	12 in.	15 in.	9 in.	12 in.	15 in.
0.5	0.76	0.90	1.04	2.34	4.05	6.35
1	1.09	1.30	1.50	3.38	5.85	9.15
2	1.55	1.85	2.13	4.80	8.35	13.00
4	2.20	2.62	3.00	6.82	11.80	18.35
6	2.69	3.22	3.70	8.34	14.50	22.60
8	3.14	3.71	....	9.74	16.70	

Form 5. Bottom width 4 ft., side slopes $1\frac{1}{2}$:1

Grade, feet per thousand	Mean velocity, feet per second, for depths of			Carrying capacity, second-feet, for depths of		
	12 in.	15 in.	18 in.	12 in.	15 in.	18 in.
0.25	0.66	0.76	0.85	3.85	5.82	8.28
0.50	0.98	1.12	1.25	5.46	8.17	11.75
0.75	1.19	1.35	1.53	6.52	10.10	14.35
1	1.37	1.59	1.77	7.53	11.65	16.57
2	1.94	2.23	2.49	10.67	16.52	23.40
4	2.75	3.15	3.54	15.12	23.40	33.20
6	3.36	3.88	4.31	18.50	28.55	41.60

Form 6. Bottom width 6 ft., side slopes $1\frac{1}{2}$:1

Grade, feet per thousand	Mean velocity, feet per second, for depths of			Carrying capacity, second-feet, for depths of		
	12 in.	18 in.	2 ft.	12 in.	18 in.	2 ft.
0.25	0.71	0.90	1.08	5.29	11.1	19.4
0.50	1.01	1.30	1.55	7.57	16.1	27.9
0.75	1.24	1.60	1.91	9.30	19.8	34.4
1	1.45	1.86	2.21	10.90	23.0	39.8
2	2.06	2.63	3.13	15.50	32.5	56.4
4	2.92	3.74	....	21.90	46.2	

second or less in very fine sandy soil, loose fine silt, or lava ash to 1.5 to 2 ft. per second for light sandy loam, and 3 to 4 sec.-ft. for stiff clay loam.

FARM FLUMES

Flumes may be built without a supporting structure, in which case the flume box is supported directly on the ground, or elevated above the ground and supported by trestle construction. When supported directly on the ground, the flume box is built of wood or

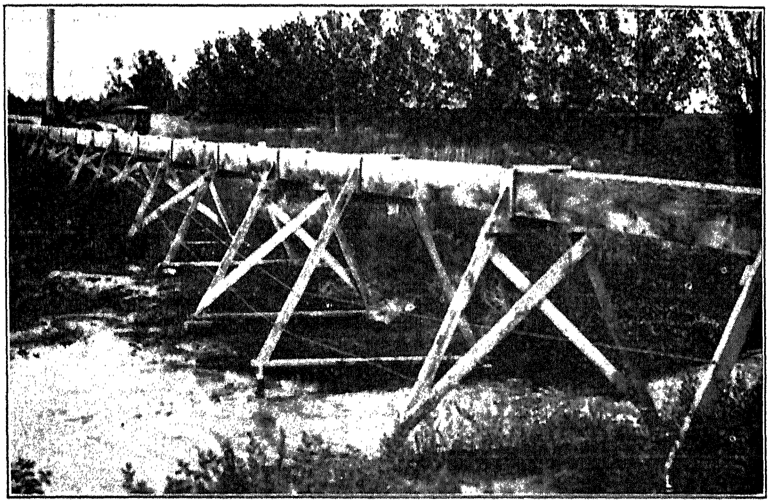


FIG. 82.—Small elevated farm flume.

concrete. This form of construction is used for field distribution to furrows, as described in Chap. VI.

Elevated flumes are used to convey water across depressions. Farm flumes generally consist of a wooden flume box on wooden posts. Some semicircular steel flumes are also used; while more expensive to construct, they are more durable and watertight. Where the topography is sufficiently rough to require the use of many elevated flumes, only small irrigating heads can be used and the capacity of the flumes required is usually less than 2 to 3 sec.-ft. Flumes of 10-sec.-ft. capacity or over may be needed occasionally for farm use. Only such small flumes are considered in this chapter; the engineering design of large flumes is discussed in Vol. II.

Figure 82 is a typical small wooden flume having a flume box consisting of three pieces supported directly by posts without stringers. The weight of the flume box and water is carried directly to the posts by the flume box acting as a beam. To avoid sagging and leaks, the supports should not be placed over 8 ft. apart where only one piece is used in the sides and bottom. For flumes having more than one bottom or side piece, closer spacing of supports should be used for this type of construction. Such three-board flumes are usually made of 1- to 1½-in. material with 2 by 4 posts. For larger flumes 2-in. material and 4 by 4 posts may be used. A good batter should be used to avoid overturning due to wind action; additional resistance to overturning may be secured by guying to a buried anchor under the flume. As the weight on each post is not large, footings may consist of wooden blocks, rock slabs, or small concrete blocks. Better usefulness of the material with larger carrying capacity is obtained by placing the side pieces of the flume box at the edges of the bottom piece rather than setting them on it.

A well-built larger flume with stringers is shown in Fig. 83. The weight of the flume box and water is carried to the stringers at 3 ft. 9 in. intervals through the collars. The use of stringers permits increasing the span between supports to 15 or 16 ft., the saving in lumber in the supporting bents balancing that required for the stringers where the flume has much height. Where more than one piece is used in the sides or floor of the flume box, watertightness may be secured by splines, battens, or calking. While such methods are usual in large flumes, ordinary lumber is generally used in farm flumes without special provisions against leakage. Transverse bracing for stiffness against lateral wind action should be used in each bent. Longitudinal diagonal bracing assists in maintaining uniform grade if settlement of a footing occurs but on firm ground is not required in short straight flumes, as the inlet and outlet give adequate longitudinal support. Footings may be of wood, stone, or concrete. For the size of flume shown in Fig. 83, 4 by 4 posts, caps, and sills could be used; however, the 6 by 6 material shown gives a more durable and rigid construction.

To connect the ends of the flume with the earth ditch, the flume ends should be carried well into the firm ground and connected with cut-off walls and wings, around which the material is well puddled. Where the velocity in the flume is to be much

greater than in the ditch, the slopes and bed of the ditch at the outlet should be protected with stone riprap or a section of concrete lining 2 or 3 in. thick about 10 ft. in length. To pass from a lower velocity in the ditch to a higher velocity in the flume, it is necessary to have the water surface at the inlet of the flume

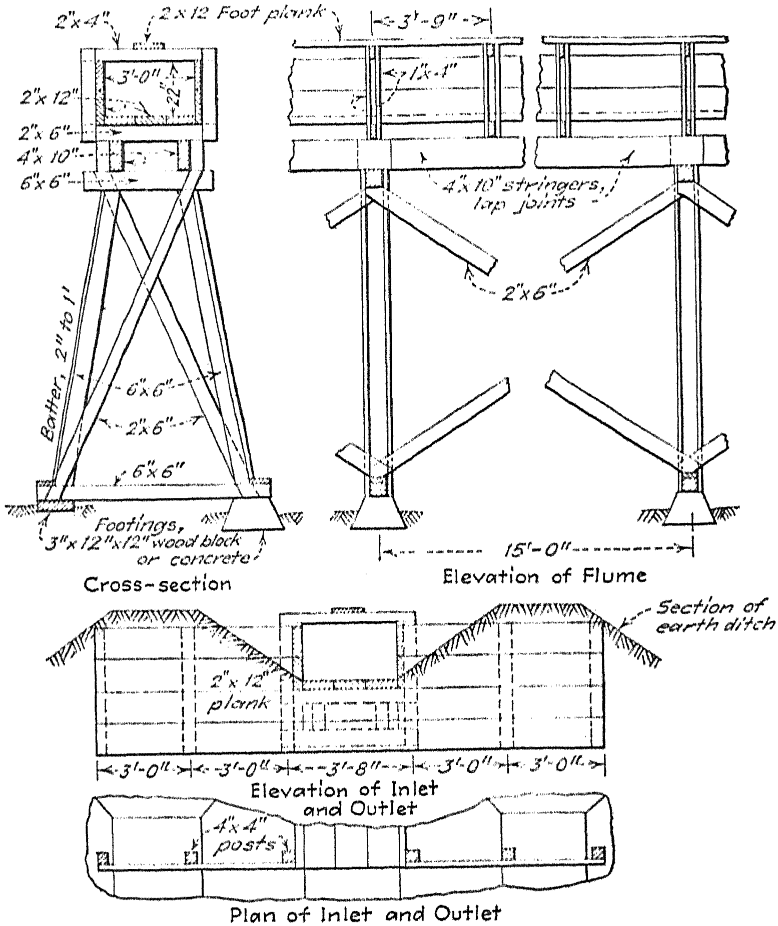


FIG. 83.—Farm flume of heavy construction.

low enough to obtain sufficient fall from the water surface in the ditch to cover entry losses and the increase in velocity head. In passing from a 2 ft. per second velocity in the ditch to a 4 ft. per second velocity in the flume, this fall should be about 3 in.; in passing from a 2-ft. velocity to a 6 ft. velocity, it should be

about 8 in. Where the change in velocity is large, the inlet and outlet should be shaped so as to change the velocity gradually. For short flumes it is preferable to use a large enough flume box so that no large change in velocity is required. For longer flumes the saving in the size of the flume for higher velocities exceeds the corresponding increase in costs of the inlets and outlets. About two-thirds of the difference in velocity head required at the inlet of the flume can be recovered at the outlet if the flume is built so that the water surface in the outlet canal is above the water surface in the flume at its outlet by that amount. Such recovery of velocity head at the outlet results in less tendency toward erosion in the canal below the outlet.

TABLE XXV. CARRYING CAPACITIES OF SMALL RECTANGULAR WOODEN FLUMES

Size 1. Inside width = 10 in.

Grade, feet per 1,000 ft.	Mean velocity, feet per second, for depths of		Carrying capacity, second-feet, for depths of	
	3 in.	6 in.	3 in.	6 in.
1	0.89	1.13	0.19	0.47
2	1.27	1.62	0.26	0.67
3	1.56	2.00	0.32	0.83
4	1.80	2.31	0.37	0.96
5	2.01	2.59	0.42	1.08
6	2.22	2.83	0.46	1.18
8	2.55	3.27	0.53	1.36
10	2.86	3.66	0.60	1.52

Size 2. Inside width = 12 in.

Grade, feet per 1,000 ft.	Mean velocity, feet per second, for depths of			Carrying capacity, second-feet, for depths of		
	3 in.	6 in.	9 in.	3 in.	6 in.	9 in.
1	0.93	1.21	1.39	0.23	0.60	1.04
2	1.32	1.73	1.98	0.33	0.86	1.48
3	1.62	2.13	2.44	0.40	1.06	1.83
4	1.87	2.45	2.82	0.47	1.22	2.12
5	2.09	2.75	3.16	0.52	1.38	2.37
6	2.29	3.01	3.46	0.57	1.50	2.60
8	2.65	3.48	4.00	0.66	1.74	3.00
10	2.97	3.90	4.47	0.74	1.95	3.35

TABLE XXV.—CARRYING CAPACITIES OF SMALL RECTANGULAR WOODEN FLUMES.—(Continued)

Size 3. Inside width = 18 in.

Grade, feet per 1,000 ft.	Mean velocity, feet per second, for depths of			Carrying capacity, second-feet, for depths of		
	6 in.	9 in.	12 in.	6 in.	9 in.	12 in.
0.5	0.96	1.16	1.27	0.72	1.31	1.90
1.0	1.39	1.66	1.84	1.04	1.87	2.76
1.5	1.71	2.04	2.26	1.28	2.30	3.40
2	1.98	2.37	2.63	1.49	2.67	3.95
3	2.44	2.91	3.23	1.83	3.28	4.85
4	2.82	3.37	3.73	2.12	3.80	5.60
5	3.16	3.77	4.18	2.37	4.25	6.25
6	3.46	4.12	4.57	2.60	4.64	6.85
8	4.00	4.77	5.29	3.00	5.38	7.95
10	4.47	5.33	5.91	3.35	6.00	8.85

Size 4. Inside width = 24 in.

Grade, feet per 1,000 ft.	Mean velocity, feet per second, for depths of			Carrying capacity, second-feet, for depths of		
	6 in.	9 in.	12 in.	6 in.	9 in.	12 in.
0.5	1.05	1.27	1.44	1.05	1.90	2.88
1	1.51	1.84	2.06	1.51	2.76	4.12
1.5	1.86	2.26	2.52	1.86	3.40	5.04
2	2.16	2.63	2.93	2.16	3.95	5.86
3	2.65	3.23	3.60	2.65	4.85	7.20
4	3.06	3.73	4.16	3.06	5.60	8.32
5	3.43	4.18	4.65	3.43	6.25	9.30
6	3.75	4.57	5.10	3.75	6.85	10.20
8	4.34	5.29	5.89	4.34	7.95	11.78
10	4.85	5.91	6.58	4.85	8.85	13.16

Carrying Capacity of Flumes.—The carrying capacities of different sizes of rectangular wooden flumes are given in Table XXV. These are computed with Kutter's formula using a coefficient of roughness of 0.014. The capacities shown should be obtained with flumes in average condition. If poorly maintained, worn, or silted, the carrying capacity may be 10 to 15 per cent less than the amounts shown in Table XXV. The carrying capacity of rectangular concrete flumes of the usual roughness of

farm construction may be obtained from the same table by deducting 5 per cent from the amounts given for the different sizes and slopes. The depths shown in Table XXV are the depths of water in the flume; the flume boxes must be sufficiently deeper to provide the necessary freeboard of 3 to 6 in. for the different sizes.

PIPES FOR FARM DISTRIBUTION SYSTEMS

Pipes are used in the conveyance and distribution of irrigation water on farms for the following purposes:

1. In place of earth ditches to convey the water to the different parts of the farm, such as the use of cement-, wood-, or steel-pipe systems of irrigation. Such pipes may be used to cross depressions as inverted siphons or as delivery lines under pressure where water is pumped to the higher parts of the land, as well as for distribution to furrows.

2. For application of water by the surface-pipe method of irrigation with detachable slip-joint metal pipe as described in Chap. VI.

3. For field distribution lines for delivery to furrows, also as described in Chap. VI.

Concrete Pipe.—The pipe so extensively used in California, and to some extent in the other states, is usually made in sections 2 to 2½ ft. long (Fig. 84). One end of the pipe tapers in and the other end tapers out so that the pipes when joined form a beveled lap joint of the same thickness as the rest of the pipe. A collar of mortar is placed around the joint to hold it in place and give watertightness. This form of joint is preferred to the bell joint used with sewer pipe, as the straight exterior of the pipe is easier to cast and to lay. The pipe is made by tamping the concrete in collapsible metal molds, which stand on end. In order to be able to remove the mold promptly after casting, dry mixtures are used of one part of cement to three or four of sand and small gravel. After casting, the pipe is removed to the curing yard, the form removed, and the pipe kept moist by sprinkling for at least one week to secure proper curing. The pipe should be aged for 30 days before laying. The concrete may be hand-tamped in the molds; machine tamping is now more usual at permanent plants. The less carefully made hand-tamped pipe formerly generally used was not suitable for use under pressures that would result in tensile stress in the pipe of over 25 lb. per

square inch, or 10- to 15-ft. pressure heads for the sizes from 12 to 18 in. Standard pipe 8 to 14 in. in diameter, as now made, may be used satisfactorily for pressure heads up to 40 ft.

To obtain good pipe requires careful and experienced workmanship, and it is usually preferable for the pipe to be made and laid

FIG. 84.—Laying concrete pipe.

by a reliable contractor rather than for the landowner to acquire the equipment and do the work for himself.

Where concrete-pipe distribution systems are used, the head handled is usually not over 2 sec.-ft. and frequently is less than 1 sec.-ft. Field distribution lines are usually 8 to 12 in. in diameter, with some systems using 6-in. pipe and some as large as 18 in. It is usually advisable to select the size of pipe so as to have some margin of capacity, as the costs increase much more slowly with increase in size than the increase in carrying capacity.

Average costs for general California conditions are shown in Table XXVI. Costs for individual systems will vary with the location and other items. The costs in Table XXVI represent

typical general figures for areas where pipe is available with short distances of haul and are relatively consistent for the different sizes. In any area where much pipe is being used, there are usually local pipe contractors from whom direct local quotations can be readily obtained.

TABLE XXVI.—TYPICAL COSTS PER LINEAL FOOT OF ORDINARY CONCRETE PIPE FOR CALIFORNIA CONDITIONS

Diameter of pipe, inches	Cost of pipe at yard, cents	Cost of hauling, cents	Cost of laying, cents	Cost of ditching and backfilling, cents	Total costs, cents
6	20	2	6	5	33
8	22	3	6	5	36
10	25	4	7	5	41
12	30	4	8	6	48
14	40	5	9	8	62
16	50	6	10	10	76
18	65	8	12	11	96

The distributing and control stands used with concrete-pipe systems for furrow irrigation have been discussed in Chap. VI. In the division of flow between supply and distributing pipe lines, gates are required. Where water is obtained by pumping from wells directly into pipe lines, or above closed gates in the pipe line, vents are desirable. Such vents consist of open vertical pipe rising above the hydraulic grade line.

Where open division boxes are used, slide or pressure gates such as those described in Chap. VI are used. Hub end gates inserted in the pipe line, with the gate, when open, recessed into the upper part of the gate frame, are also used. These gates cost about $25 for 8-in. size and $35 for the 12-in.

Vitrified-clay Pipe.—Vitrified-clay pipe may be used for farm irrigation systems in locations near kilns where it may be obtainable at costs comparable with concrete pipe. It can withstand pressures similar to those for concrete pipe, is more brittle, and has bell and spigot joints. It has been used where it was difficult to secure concrete pipe of good quality or in alkali ground where it is more resistant to the action of alkali than concrete. The extent of its use for farm irrigation systems is relatively small. General prices per lineal foot for vitrified pipe vary from about 20 cts. for 6-in. pipe to 50 cts. for pipe 12 in. in diameter.

Wooden Pipes.—The wooden pipes ordinarily used on the farm are the factory-made machine-banded pipe consisting of wooden staves with radial edges bound tightly together by wires spirally wound continuously around the pipe. Larger wood-stave pipes are built in place but sizes used for farm systems are factory-made in variable lengths up to 24 ft. and jointed in the field with inserted joints. The pipe is dipped in hot asphalt and rolled in sawdust to form a protective coating. Cast-iron connections and valves are used. Small takeouts are screwed directly into the staves.

General Pacific Coast prices for coated machine-banded wood-stave pipe capable of carrying 50- to 75-ft. pressures are as follows:

Diameter of pipe, inches.......	6	8	10	12	14	16	18
Cost of pipe per lineal foot.....	$0.45	$0.55	$0.65	$0.75	$0.90	$1.05	$1.20

Where laid in trenches, the cost of trenching is similar to that for concrete pipe; the cost for laying is relatively small.

Steel Pipes.—Steel pipes commonly used for farm irrigation systems are made of steel sheets rolled and riveted or welded longitudinally or spirally. Each section of pipe is usually 20 to 25 ft. in length. Slip joints are used for low pressures and bolted, flanged, or welded joints for high pressures. The pipe is usually protected against rust by galvanizing or by a tar or asphalt coating. Special low-pressure fittings and valves are used for irrigation which have a much lower cost than the similar fittings required for high pressures.

General prices for steel slip-joint pipe safe for pressure heads up to 200 ft. for Pacific Coast conditions are as follows:

Diameter of pipe, inches............	4	6	8	10	12	14	16	18	20	22	24
Gage of metal.......	16	16	16	14	14	12	12	12	10	10	10
Price per lineal foot.	$0.25	$0.35	$0.45	$0.65	$0.75	$1.10	$1.25	$1.40	$2.00	$2.15	$2.30

Carrying Capacities of Pipes.—The usual carrying capacities of different sizes of concrete pipe are shown in Table XXVII. Table XXVII is computed from the Scobey formula, using a coefficient of 0.310 for modern pipe made by the dry-mixture process. These capacities should be obtained with well-laid pipe of average quality. The carrying capacity for vitrified-

clay pipe is about the same as that of concrete pipe. Wood-stave pipes have a capacity about 10 per cent larger than the values given in Table XXVII for low velocities to 25 per cent larger at high velocities. Riveted steel pipe will carry from about 5 to 10 per cent less than concrete pipe at low velocities to about the same capacity at higher velocities.

The loss of head at the inlet and outlet, due to velocity head changes and irregular currents resulting from the change in cross section in passing from one form of channel to the other, have not

TABLE XXVII. CARRYING CAPACITIES IN SECOND-FEET OF CONCRETE PIPE LAID IN SECTIONS 2 FT. LONG. HEAD REQUIRED FOR FRICTION IS EXCLUSIVE OF INLET AND OUTLET LOSSES

Head required for friction, feet per 1,000 ft. of pipe	Diameter of pipe, inches								
	6	8	10	12	14	16	18	21	24
	Carrying capacity of pipe when running full, second-feet								
0.5	0.13	0.28	0.50	0.81	1.22	1.73	2.36	3.54	5.03
0.6	0.14	0.31	0.55	0.89	1.33	1.90	2.58	3.87	5.50
0.7	0.15	0.33	0.60	0.97	1.45	2.05	2.79	4.19	5.95
0.8	0.17	0.35	0.64	1.02	1.54	2.19	2.98	4.47	6.35
0.9	0.18	0.38	0.68	1.09	1.64	2.32	3.16	4.75	6.75
1.00	0.19	0.40	0.71	1.15	1.73	2.45	3.34	5.00	7.10
1.50	0.23	0.48	0.86	1.40	2.11	3.00	4.06	6.10	8.70
2.00	0.26	0.56	1.01	1.62	2.44	3.47	4.70	7.07	10.03
3.00	0.32	0.69	1.23	1.99	2.98	4.24	5.77	8.65	12.30
4.00	0.37	0.79	1.43	2.30	3.45	4.90	6.66	10.00	14.20
5.00	0.42	0.89	1.60	2.57	3.86	5.48	7.43	11.18	15.90
6.00	0.46	0.97	1.75	2.82	4.23	6.00	8.15	12.25	17.40
7.00	0.49	1.05	1.89	3.05	4.57	6.50	8.82	13.23	18.85
8.00	0.53	1.12	2.02	3.26	4.88	6.95	9.42	14.14	20.00
9.00	0.56	1.19	2.14	3.46	5.18	7.35	10.00	15.00	21.30
10.00	0.59	1.25	2.24	3.65	5.45	7.75	10.55	15.80	22.50
12.00	0.65	1.37	2.47	4.00	6.00	8.50	11.55	17.30	24.65
14.00	0.70	1.48	2.67	4.32	6.45	9.18	12.50	18.70	26.60
16.00	0.75	1.59	2.86	4.61	6.90	9.80	13.32	20.00	28.42
18.00	0.79	1.68	3.02	4.90	7.30	10.40	14.15	21.20	30.20
20.00	0.83	1.78	3.19	5.15	7.70	10.95	14.90	22.30	31.80
25.00	0.93	1.97	3.57	5.75	8.63	12.25	16.70	25.00	35.50
30.00	1.02	2.18	3.90	6.30	9.40	13.40	18.25	27.40	39.00

been included. This loss of head is dependent on the amount of the change in velocity and the form of the inlet and outlet structures; the allowance to be made is considered in the discussion of siphons and culverts.

SIPHONS

The type of irrigation structure usually called a "siphon" is not a true siphon but is an inverted siphon. Inverted siphons are used where the land is rolling and it is necessary to carry the water from one ridge or knoll to another, to carry water under a stream, or to cross under a lower ditch or roadway. Siphons convey water across the depression in a pipe which is connected at the upper and lower ends to inlet and outlet structures. The flow through the siphon depends on the difference in elevation between the inlet and outlet, the size and roughness of the conduit, and the form of the inlet and outlet. Where the siphon is very short, it is practically a culvert, and the table of flow given for culverts may be used. For longer siphons it is necessary to consider the additional frictional resistance due to the greater length of pipe.

The required difference in elevation between the water surfaces of the inlet and outlet to produce a certain discharge through a siphon with a conduit of a fixed diameter may be obtained by adding to the difference in levels for a short culvert, as given in Table XXVIII, the fall between the inlet and outlet required to overcome the frictional resistance in the additional length of pipe which can be obtained from Table XXVII. The inlet must be set low enough to place it below the water surface after allowance has been made for all entry losses.

Figure 85 illustrates portions of typical siphons. The inlet and outlet walls are usually built alike. Where soil will puddle well, the simplest form of construction is obtained by ending the pipe in a breast wall at right angles to the line of the canal, the wall being carried well into the banks on each side and 18 to 24 in. below the bottom of the ditch. To form a tapered or funnel-shaped inlet or outlet and to protect the section of the ditch adjacent to the outlet from erosion, the sides and bottom of the ditch may be lined for a few feet with rock riprap or with a concrete lining 2 to 3 in. thick, ending in a cut-off wall about 12 in. deep. Where the soil is loose or on steep slopes where there is danger of washing under or around the inlet or outlet, the pipe

may be carried farther into the ditch and more extensive cut-off walls and floor used. Inlet and outlet structures may be made of wood or of concrete either plain or reinforced. For the sizes used

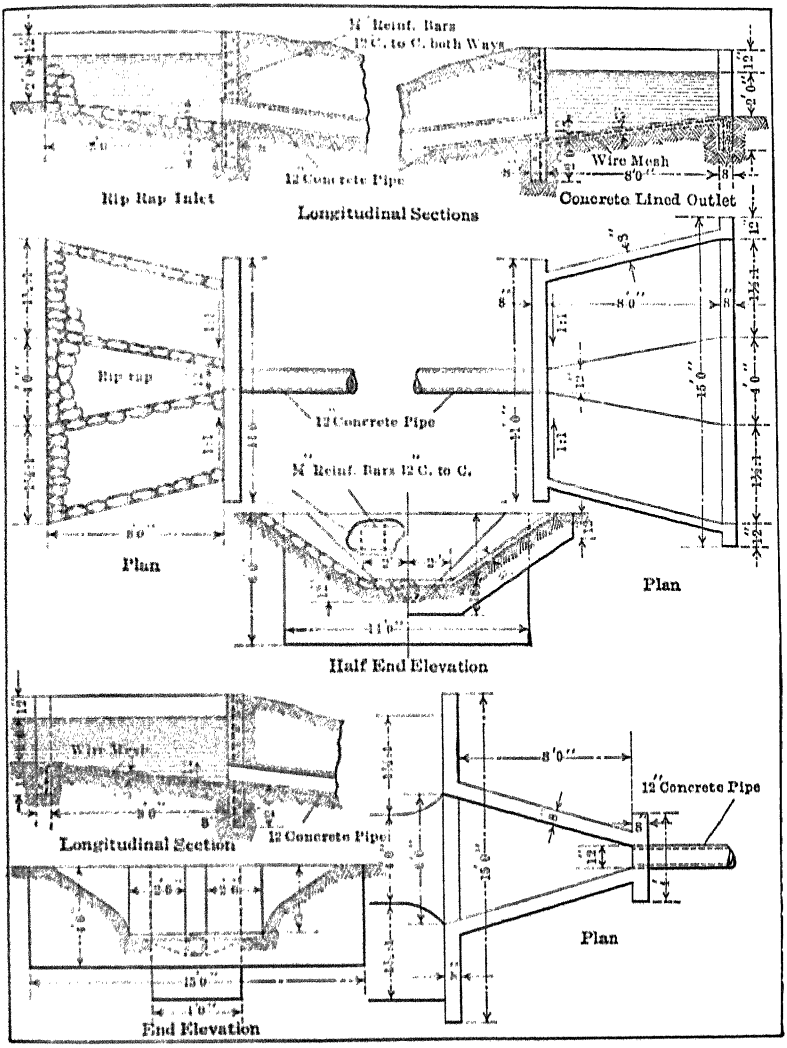


FIG. 85.—Details of typical small siphons.

in farm systems, reinforcing is not usually required except in soft ground or where temperatures much below freezing occur.

The conduit of the siphon is generally a concrete, vitrified-clay, wood, or steel pipe. The plain concrete pipe, of the type

previously described, and vitrified clay cannot be used where the pressure head exceeds the values which have been given. Reinforced-concrete pipe may be used for large pressures but for small sizes steel or wood pipe is preferable for such conditions. The design of larger siphons and a more complete discussion of reinforced-concrete and wooden pipes are taken up in Vol. II.

STRUCTURES USED ON FARM DITCHES

The type and sizes of structures used on farm distribution systems depend on the size of the ditches and the method of irrigation. To regulate and control the water in the ditches, the following structures may be required: (1) head gates for field ditches; (2) division boxes to divide the water between two ditches; (3) check gates to regulate and raise the water level in the ditch in order to permit diversion from the ditch into one or more field ditches, or to deliver water on the land through cuts in the banks or through levee gates; (4) drops to absorb the excess in grade, when the slope of the land on the line of the ditch is larger than the grade which may be used in the ditch without producing an excessive velocity; (5) levee gates to control the water delivered from a ditch through an opening made in the bank of the canal, or in the levee of a check; (6) culverts and bridges for road crossings; (7) stock guards. Some of these structures may be combined such as drop, checks, and division boxes.

The smaller structures used for wild flooding and for distribution to furrows have been discussed in Chap. VI in connection with these methods of irrigation. The structures described in this chapter are those more generally applicable to the larger farm ditches, such as those used with the different check methods of irrigation. Examples of typical structures for various conditions of use are presented.

Farm structures may be of wood or concrete construction. While of shorter life and consequently higher ultimate costs for permanent use, wood is generally used for such structures. However, concrete is coming into more general use as the farm systems are improved along with the improvement of other farm construction.

Wood structures may be built of either 1- or 2-in. material. For all except the larger structures used on the farm, 1-in. material is sufficiently strong for use in walls and floors. How-

ever, its useful life is short, and structures built of light material warp and lose shape more quickly so that 2-in. material is more economical except for some small structures. Use of 2-in. material in place of 1-in. does not double the cost of the structure, as excavation and the labor in framing the structure are only slightly increased with the heavier lumber. For cross walls 2 by 4 posts and braces would be used with 1-in. boards and 4 by 4's with 2-in. plank.

The loads carried by farm structures do not require thick walls where concrete is used. Where concrete is placed directly on the ground as in floors or linings, thicknesses suited to the needs can be used. For such uses thicknesses of $1\frac{1}{2}$ to 2 in. are used where free from frost action or impact; 4 to 6 in. may be used under conditions of severe service. Where concrete is used in vertical walls and placed between forms, there is no economy in using thicknesses of less than 4 in., as the value of the material saved is balanced by the difficulty of securing good tamping in narrow forms. With reinforcing there is little economy for thicknesses less than 6 in. Where many structures of the same size are required, the designs may be standardized and precast slabs used. These are cast on their side, cured, and later placed in the structure. For such structures some reinforcing is used to give strength in handling. Thicknesses of 2 in. are usual.

Concrete farm structures are built of both plain and reinforced concrete. For mild climates, reinforcing is not usually required for strength. Some light reinforcing may be desirable as a tie in case of cracking or uneven settling. Light rods or some type of mesh are used. Where used, reinforcing is usually placed in the center of the concrete in these structures except in crosspieces planned as beams.

HEAD GATES

The head gate for delivery from the canal system to the farm is usually installed and controlled by the canal organization and is not a part of the farm distribution system. The types used are described in Vol. III. For farm reservoir outlets or on larger farms for takeouts of farm laterals, similar head gates may be used. These may consist of closed conduits through the bank, consisting of wooden boxes or various kinds of pipe with a gate at the inlet end or of open-top structures with gates or flashboards.

DIVISION BOXES

At division points on farm-supply ditches, control structures of permanent rather than movable type are usually installed. A

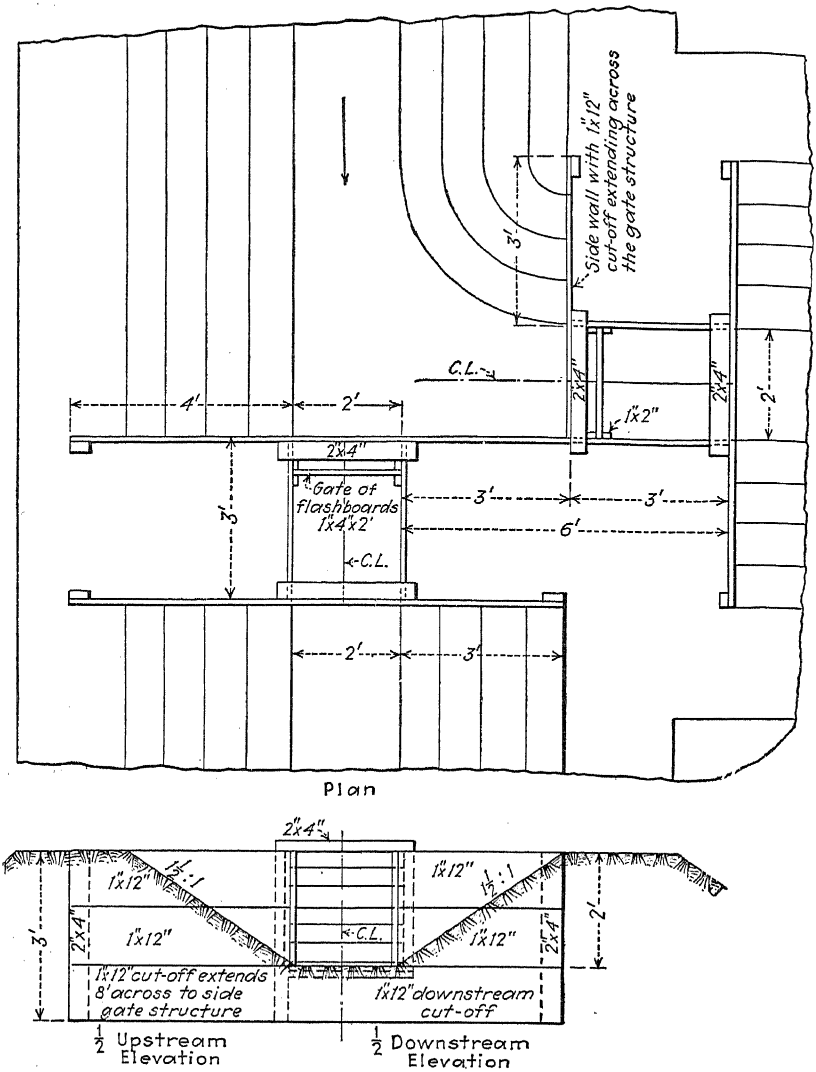


FIG. 86.—Wooden division box for 2-ft. ditch.

gate across both channels is usually required in order to control the division of the flow. For ditches of 2-ft. bottom width or

less, wooden structures of 1-in. material similar to that shown in Fig. 86 are adequate. For larger ditches, wooden structures of 2-in. lumber or concrete structures are used. The use of the two gates in one structure permits a saving in wing walls compared with two separate gate structures. Division boxes may also serve as check gates.

CHECK GATES

Check gates are used to control the water upstream from the structure so as to permit delivery from the ditch on to adjacent land or into other ditches. Such structures may be combined with drops where it is desired to remove surplus grade from the ditch.

The most essential feature of a check-gate structure is the cut-off wall. Unless this effectively cuts off all seepage under or around the structure, washing out is liable to occur. For smaller structures, a 12-in. depth of cut-off should be used. For ditches with depths of water of 2 to 3 ft., a depth of cut-off of 18 to 24 in. is desirable. The larger depths of cut-off should be used in sandy soils. The wing walls should extend to the center of the ditch bank and should be as high as the top of the bank.

Different types of gates may be used. The gate opening may be closed with a built-up gate with handle as in Fig. 87. When it is desired to raise the elevation of the water upstream from the gate and also to permit part of the flow to pass through the structure, the gate is raised until the flow it is desired to pass will discharge through the opening under the pressure of the upstream water elevation. This gives flow through the lower part of the gate opening or underflow discharge. Another method of controlling the flow is to use separate gate pieces or flashboards fitting in the gate guides as in Fig. 88. The gate opening is closed by placing such number of flashboards as may be required to give the desired upstream water elevation. Flow through the structure then occurs as overpour over the top flashboard. Control by overpour permits a closer regulation of the upstream water elevation with variations in the supply. The energy of the water passing through the gate is also more easily dissipated with less tendency to erode below the structure.

The gate groove may be set vertically or inclined downstream (Fig. 88). The inclined groove gives less tendency for the gate to float out and it is easier to prevent leakage by shoveling earth on

its upstream side. Vertical gate grooves may be set within the box structure as in Fig. 86, or on the upstream face of the wing wall as in Fig. 88.

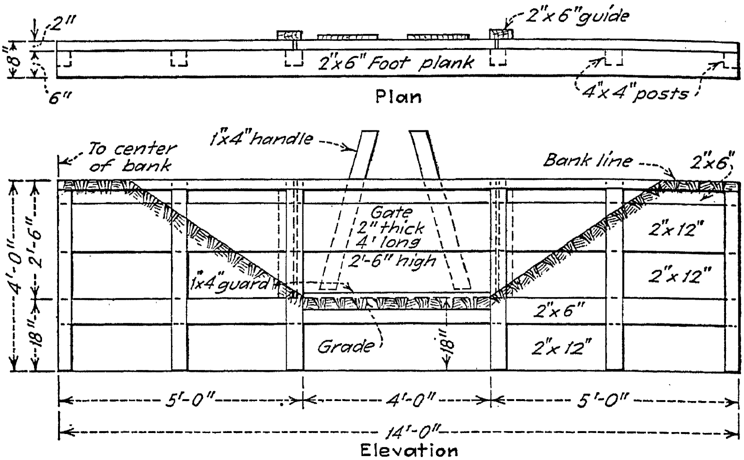


FIG. 87.—Single-wall check gate for 4-ft. ditch.

The width of gate opening is usually the same as the bottom width of the ditch. This gives a large enough area of gate open-

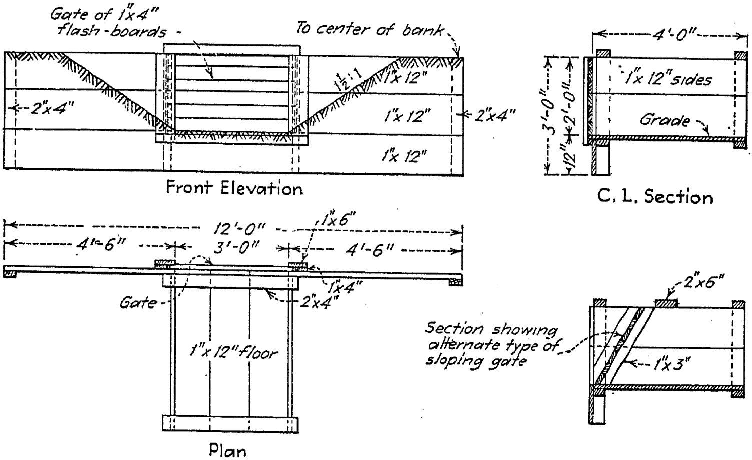
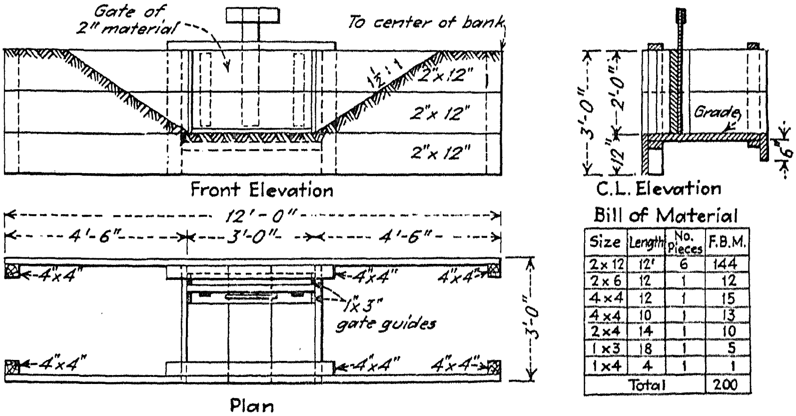


FIG. 88.—Check gate with side walls and floor for 3-ft. ditch using 1-in. lumber.

ing to avoid excessive velocities. Gate openings up to 6 ft. in width can be handled as a single opening, although a center post with two gates may be used for ditches 5 to 6 ft. wide.

A single-wall wooden check gate for use in an earth ditch of 4-ft. bottom width is shown in Fig. 87. This type of structure is suited to check gates for ditches of this size or smaller, when used to hold water back for delivery above the structure for the following conditions: (1) where the entire flow is checked, (2) when part of the water is passed through the structure and the downstream water level is checked back to submerge the gate sill, (3) for short periods of use in resistant soils when water is discharged through the gate without downstream submergence. It is the simplest form of construction, as it consists merely of the wall across the



Bill of Material

Size	Length	No. Pieces	F.B.M.
2x12	12'	6	144
2x6	12	1	12
4x4	12	1	15
4x4	10	1	13
2x4	14	1	10
1x3	18	1	5
1x4	4	1	1
Total			200

FIG. 89.—Double wing-wall check gate for 3-ft. ditch using 2-in. lumber.

ditch and sufficient framework to form the gate support. The structure shown consists of 2-in. lumber and 4 by 4 posts. For smaller structures, 1-in. material may be used.

A light-weight wooden check gate for a 3-ft. ditch is shown in Fig. 88. To protect against erosion below the gate, a short length of flume box is attached to the downstream side of the head wall. The length of such side walls and floor varies from a minimum of 3 ft. for small ditches to an amount equal to or somewhat larger than the bottom width of the ditch for ditches up to 6 ft. in width. This type of check gate is adapted to structures in medium soils, where the period of use of the check gate or the passage of part of the flow when in use would cause erosion.

A double wing-wall check gate is shown in Fig. 89. The downstream wing wall provides protection against erosion from below of the backfill around the side walls. It is a preferable form o construction for sandy soils or for very heavy soils which tend t

crack when dry, as the backfill can be puddled between the two wing walls. The downstream wing wall should extend well into the ditch banks but needs to be only deep enough to prevent erosion from the flow leaving the structure.

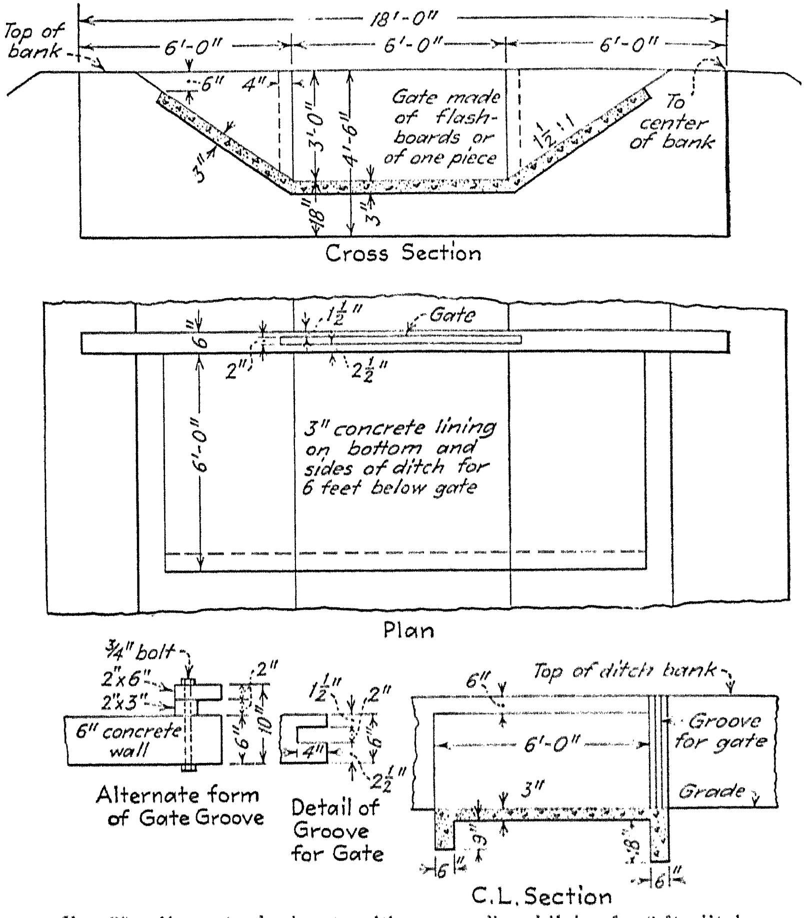


FIG. 90.—Concrete check gate with cross wall and lining for 6-ft. ditch.

A concrete check gate is shown in Fig. 90. This consists of a cross wall containing the gate with a section of concrete lining on the downstream side to prevent erosion. Such protection is more economically constructed as a lining on the cross section of the ditch than as side walls cast in forms. A thickness of lining of 3 in. is adequate; where little water passes the structure when in use as a check or for mild climatic conditions, a 2-in. thickness may be

sufficient. A double wing-wall concrete check gate is shown in Fig. 91.

DROPS

Where the gradient of the ditch produces velocities that cause erosion, the excess fall is concentrated at drop structures. For farm ditches the fall at each structure does not usually exceed 2 ft., the structures being spaced at such intervals as the slope may require. Drops may be combined with check gates where checking up for delivery is also required.

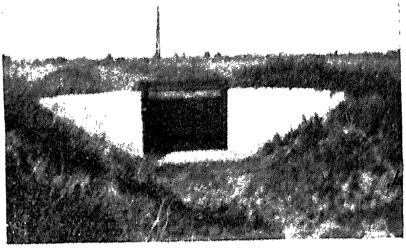


FIG. 91.—Double wing-wall concrete check gate.

A typical drop for a 3-ft. ditch is shown in Fig. 92. As the difference in elevation of the water surface above and below the structure is larger than for check gates, a somewhat deeper cut-off should be used. The same general types of single-wall, wall-and-box,

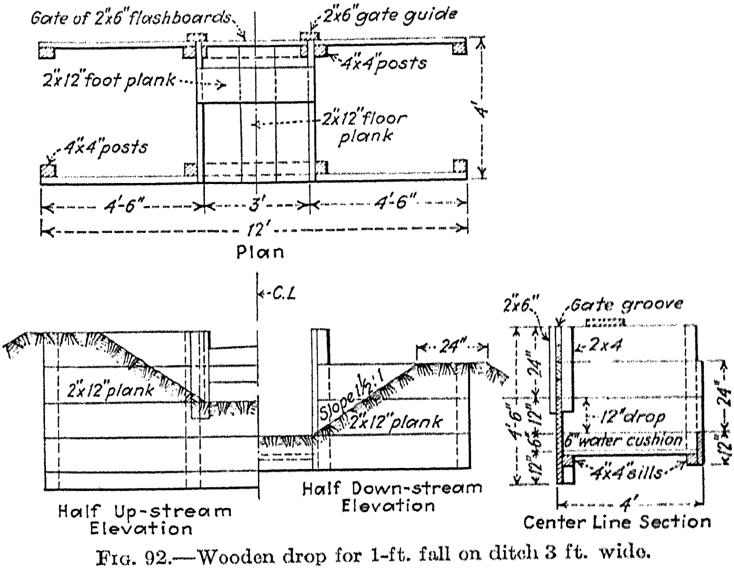


FIG. 92.—Wooden drop for 1-ft. fall on ditch 3 ft. wide.

and double wing-wall construction may be used as those illustrated for check gates. The single-wall structure is seldom suitable for use as a drop due to the lack of protection against

downstream erosion. The floor may be depressed below the grade of the ditch on the downstream side of the structure to form a water cushion for the water passing the gate as in Fig. 92. The length of boxing for drops should be somewhat greater than that for check gates owing to the greater energy of the falling water to be dissipated.

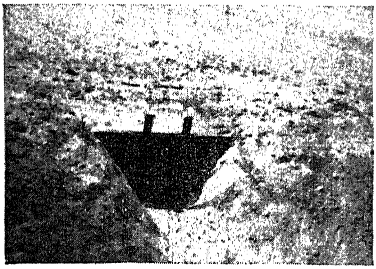


FIG. 93.—Single-wall wooden levee gate.

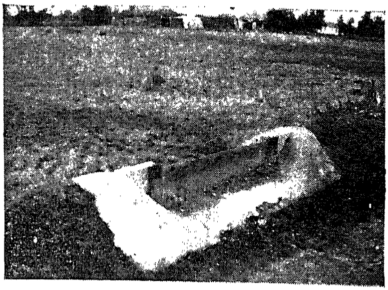


FIG. 94.—Concrete levee gate for delivery into border checks.

LEVEE GATES

This term is used to describe the structures set in the ditch banks to control flow into the adjacent checks. For such delivery the water in the field ditch needs to be held a minimum of 6 in. above the elevation of the adjacent land on which delivery is to be made.

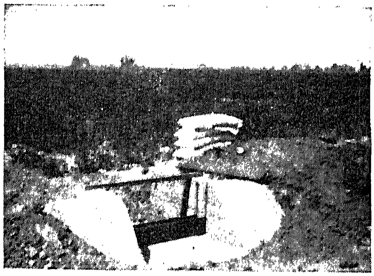


FIG. 95.—Concrete levee gate using double flashboards for the gate.

The gate area can be adjusted to the flow to be delivered into each check. Such area is preferably obtained mainly as width, rather than as depth of flow. The gate sill should be placed at or somewhat below the level of the adjacent land. If placed at the elevation of the bottom of the ditch a larger area of gate opening is obtained, but leakage when not in use is increased and the

structure is more expensive. The width of gate opening should be adjusted to the depth of flow and discharge, so that the velocity through the gate opening does not exceed 3 ft. per second in order to avoid erosion of the land adjacent to the gate.

Similar types of grooves and gates are used as for check gates. The cut-off wall is usually placed at the center of the ditch bank. As the water pressure against the structure is less than that for drops or check gates, somewhat less depth of cut-off can be used.

A single-wall wooden levee gate is shown in Fig. 93. This requires a longer wall than where the ends of the cut through the ditch bank are supported by side walls. A levee gate with a

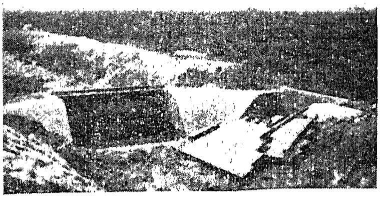


Fig. 96.—Combined concrete check gate and levee gate, showing forms used for cross walls.

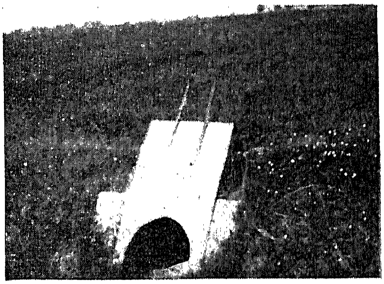


Fig. 97.—Concrete-pipe levee gate with sloped head wall.

single concrete wall containing the gate set in a plastered opening in the ditch bank is shown in Fig. 94. A concrete levee gate with a double flashboard is shown in Fig. 95. The space between the two flashboards can be filled with earth to prevent leakage when not in use. The ends of the ditch bank are trimmed to a vertical section and the structure built with one form at each end of the gate, the remainder of the concrete being poured against the earth surfaces. A combination of such a levee gate with a check gate is shown in Fig. 96. A concrete-pipe turnout with a concrete face slab containing the guides for a galvanized iron gate is shown in Fig. 97. These are used in diameters from 6 to 14 in. The head walls attached to a short length of pipe can be obtained from most concrete-pipe yards. Such number of lengths of pipe are added as may be needed to reach through the ditch bank. Similar turnouts, consisting of a galvanized-iron gate attached to galvanized-iron pipe extending through the ditch bank, are also

used. Such gates with 2 ft. of attached pipe cost about $2.50 for 8-in. and $3.50 for 12-in. size.

ROAD CROSSINGS

Road crossings over the permanent farm ditches are needed in handling farm equipment and crops. Such crossings may be either culverts to carry the water under the roadway or bridges which carry the roadway over the ditch. Such crossings within the farm are on private roadways and do not have the same responsibility for public safety that attaches to similar crossings on public roads. In some cases the farm delivery may be made at a distance from the farm and the farm owner may have to provide his own lateral to the farm. If such laterals cross public highways, the crossings have to meet the legal requirements of such culverts and bridges.

Farm crossings need to be only of such strength and width as may be required for the passage of farm traffic. Public road crossings have specified minimum widths, usually 16 ft., which will permit passage of vehicles on the crossings and sufficient strength to carry the traffic which may use the public highway. This requires stronger and more permanent construction. When built to comply with the county or state requirements, maintenance may be taken over by the public organization maintaining the highway.

The choice between culverts and bridges depends on the size of the ditch and the relative grades of the ditch and road. For farm roads the grade of the road may be raised to the grade of the top of the ditch bank giving clearance for a bridge without restriction on the cross section of the ditch. For public roads the ditch is usually required to cross under the road grade so that depressed culverts or siphons are frequently required. Where either may be used, culverts are more generally chosen for the smaller ditches.

Culverts consist of any suitable type of conduit with suitable inlet and outlet structures. The conduit is usually of vitrified clay, corrugated metal, concrete or wood pipe, or of wood box construction. Strength against external load is required; the internal pressures are usually too small to be a controlling factor. Types of culverts are shown in Fig. 98. An earth covering of 18 in. is needed for adequate spreading of wheel loads. Straight inlet and outlet walls are sufficient where the grade of the culvert is only slightly below that of the ditch. Where the culvert has

to be lowered under the roadway, inlet and outlet basins are required.

The capacities for culverts 20 ft. in length are shown in Table XXVIII. The difference in water-surface elevation at inlet and outlet is used largely in overcoming entry and exit losses rather than in friction in the culvert pipe. Where the difference in head

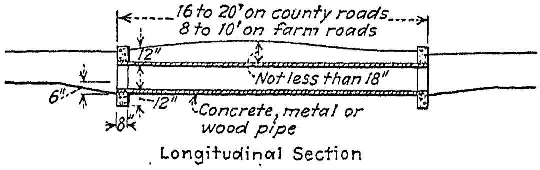


FIG. 98.—Typical road culvert for small ditches.

results in pipe velocities in excess of that which the adjacent soil can withstand without erosion, the ditch will require protection for a few feet below the outlet. Such protection may be of either concrete lining, rock riprap, or wooden box construction.

TABLE XXVIII.—CAPACITIES IN SECOND-FEET OF PIPE CULVERTS 20 FT. IN LENGTH

Diameter of pipe, inches	Difference in elevation between inlet and outlet water levels, inches					
	2	4	6	8	10	12
6	0.45	0.60	0.75	0.85	0.95	1.05
12	1.85	2.62	3.20	3.70	4.15	4.55
18	4.25	6.00	7.30	8.45	9.45	
24	7.90	11.20	13.70	15.85		

Wooden bridges used on farm ditches are of the stringer type; the span required is within the limits adapted to single spans of this type. Such bridges consist of 2- or 3-in. flooring resting on stringers at right angles to the direction of the ditch, the stringers in turn resting on wooden or concrete mud sills set in the canal bank. Figure 99 illustrates such a bridge, as used on public roads. For farm bridges, widths of 8 ft. for ordinary equipment are adequate and, for crop loads, lighter-weight construction may be used. The stringers vary from 3 by 10 for spans of 6 to 8 ft. to 3 by 14 or 5 by 12 for spans of 12 to 16 ft. Such stringers are usually spaced about 2 ft. apart.

For small farm ditches, crossings may be made by widening the ditch and flattening the side slopes so that no bridge is required.

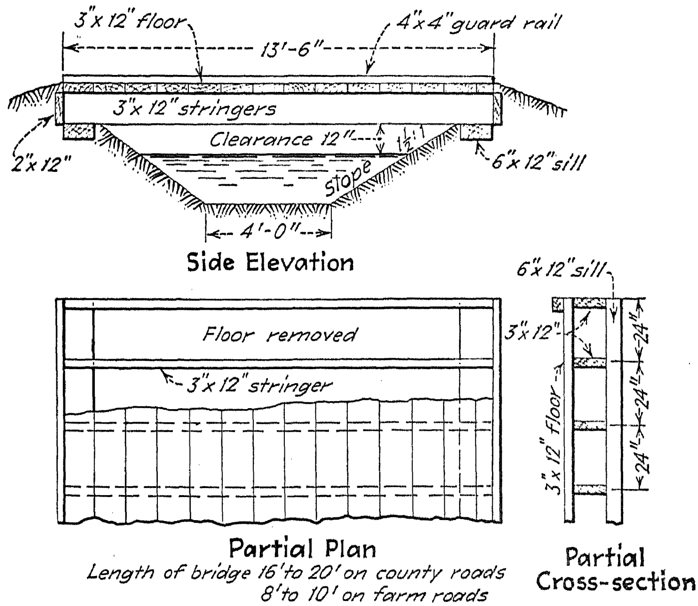


FIG. 99.—Stringer bridge for 4-ft. ditch.

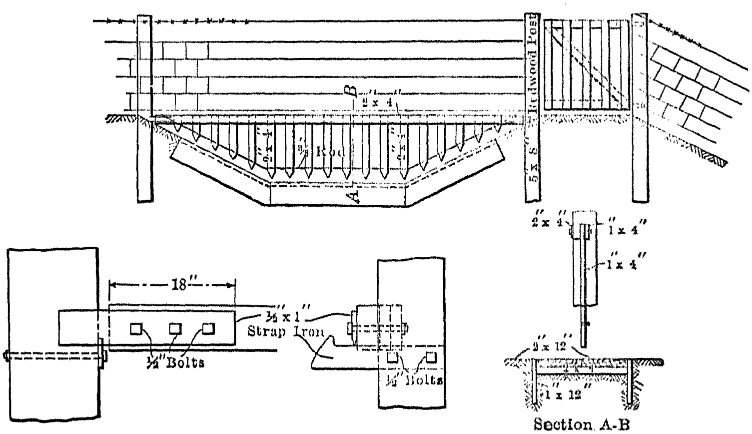


FIG. 100.—Swinging stock guard.

This is frequent practice for field ditches in the wild-flooding method, as crossing of the ditches usually occurs at times when

the ditches are not in use for irrigation. Crossings may be avoided by leaving a roadway at the lower end of the field ditches.

STOCK GUARDS

Where irrigated fields are pastured or where stock may enter or leave fields along roadways, some provisions are required for closing the opening under the fence made by the ditch. This may not be required for the smaller ditches and larger stock. Such stock guards may consist of a lower wire on the fence set to clear the water surface in the ditch or the sagging of all wires at the ditch by hanging a weight in the ditch. A swinging stock guard which will clear itself of weeds and other debris that may become caught by the guard is shown in Fig. 100. Some lining may be needed to avoid erosion of the ditch below such a guard due to the higher velocity when partly clogged.

CHAPTER VIII

THE SELECTION AND COST OF SMALL PUMPING PLANTS

Water is pumped for irrigation both from surface sources, such as streams, lakes, or canals, and from ground-water sources, such as wells. Of the area supplied from streams, over 10 per cent diverts by pumping and about 7 per cent additional supplements its stream supply from wells. The U. S. Census returns show that in 1929 over 2,000,000 acres, representing about 10 per cent of the total area irrigated, were irrigated entirely by pumping from wells; springs supplied over 200,000 acres and flowing wells nearly 50,000 acres additional. The area supplied by flowing wells decreased about 65 per cent in the 20 years from 1909 to 1929; the area supplied by pumping from wells increased over 400 per cent in the same period. The area supplied by pumping from wells increased nearly 800,000 acres from 1919 to 1929. For the same period the total area irrigated from all sources increased only about 350,000 acres, indicating that the gain in area served by pumping exceeded the decrease in area served from other sources.

Nearly 1,500,000 acres, or about three-fourths of the area served from pumped wells, is in California. Pumping from wells is also used in California as a supplemental source of supply for an additional area of nearly 800,000 acres. Louisiana and Arkansas rank second and third in area served from wells; Arizona is the only other state pumping for over 100,000 acres. Nearly half the total area served by flowing wells is in New Mexico. While the areas supplied from ground water are still small in many of the western states, future development can be expected to utilize pumping more extensively.

Pumping from wells on each farm represents a type of water supply which can be developed independently by each landowner and does not require participation with others in the construction and operation of irrigation works. While joint operation of pumping plants is often economical, the independence in time and

extent of operation of each plant is a factor that has led many to pump from ground water rather than to secure water from canals.

SOURCES OF GROUND WATER

An extensive discussion of the sources and extent of ground-water supplies is outside of the scope of this volume. Emphasis should be placed, however, on the fact that ground-water supplies, in common with surface supplies, have some definite source, move toward some outlet, and cannot furnish permanently any larger draft than the amount of the incoming supply. Ground-water supplies differ from surface streams in that pumping may temporarily draw on the accumulations of ground water and thus secure a supply in excess of the rate of replenishment, but such pumping results in progressive ground-water lowering with increased pumping lifts and costs. While it is more difficult to determine the extent of ground-water supplies than for surface streams, methods are available by which the extent of the available supply may be at least approximated. Development of any ground-water supply should proceed conservatively until its limitations have been determined. In too many areas, the ability to secure good ground-water yields by drawing on ground-water accumulations has been mistakenly interpreted as indicating large permanent supplies and has resulted in overdevelopment. The economic losses which eventually result from the necessary reductions in draft are greater than the gains during the period of use.

The quality of ground water varies more widely than that of surface streams. Variations in the quality of ground water occur between localities and in the water in different strata in the same locality. While the majority of ground waters available for irrigation is of suitable quality for such use, unless the ground water is known to be suitable from the experience of adjacent practice, the supply from new wells should be analyzed before it is used. While water of poor quality may be used for some time without noticeable effect on the crop yields, such water cannot be used permanently without injury to the land.

Flow of Water to Wells.—The yield that may be obtained from a well varies with its depth and the material through which the water moves into the well. Draft from a well results in lowering the ground water around the well. Such lowering is called the

drawdown of the well. The amount of the drawdown represents the loss of head or pressure required to overcome the friction losses of the flow of water through the surrounding material to the well. Within the limits of the capacity of a well, the yield varies with the drawdown, although each increment of discharge may

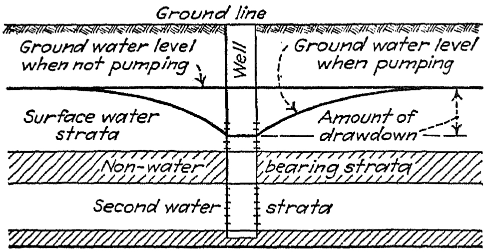


FIG. 101.—Well in water-bearing strata without pressure. Perforations in water-bearing strata only. Casing landed in dry strata.

require a larger increment of drawdown. For any well there is a limit to the economical yield. Larger yields result in too great an increase in lift; smaller yields result in too small an output in relation to the cost of the well.

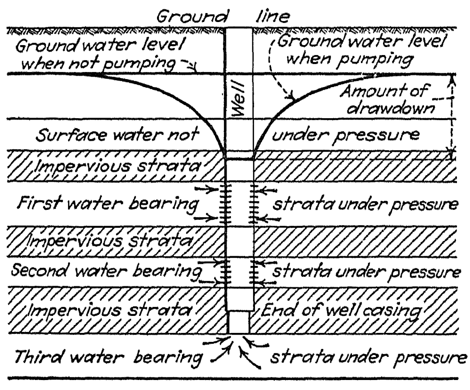


FIG. 102.—Well in water-bearing strata under pressure using both perforations and open bottom. Not perforated for surface water.

Figure 101 illustrates the drawdown in a well penetrating different water-bearing strata where the ground water occurs without pressure. The drawdown reduces the area of inflow to the well in the surface water-bearing strata. The well should be deep enough to penetrate sufficient water-bearing strata to furnish the desired yield without exceeding a reasonable amount of draw-

down. The well casing is perforated only in the water-bearing strata.

Figure 102 illustrates the flow of water to a well where the ground water is under pressure. Unless the drawdown reaches the top water-bearing strata that is perforated, no loss of inflow area occurs. The well casing is perforated in the water-bearing strata which are under pressure, the surface water which is not under pressure being excluded from the well. The well casing is landed in an impervious layer and the well bored through to the next underlying water-bearing stratum from which water is drawn through the bottom of the well. Water in different strata may be under different pressures. The pressure reduces the pumping lift required. In some areas the pressure is sufficient to cause the water to reach the ground surface, resulting in flowing or artesian wells. The yield of flowing wells may be increased by pumping.

Yield of Wells.—For irrigation use, a yield of 200 gal. per minute represents about the smallest supply that can be used economically under usual practice. For very favorable conditions in coarse water-bearing material, yields of several second-feet may be obtained. Yields of 400 to 800 gal. per minute represent typical capacities for wells used for irrigation. In coarse materials, good yields may be obtained with drawdowns of 10 to 20 ft. Many wells heavily pumped have drawdowns of over 30 ft.; in tight materials drawdowns may exceed 50 ft. For usual conditions, drawdowns of 10 to 25 ft. are typical. In tighter materials, the same yields may be secured with less drawdown, by using two or more wells spaced 10 to 20 ft. apart, connected to a single pump, as from a single well.

WELLS

Wells may be dug, bored, or drilled. Dug wells are used where the pump is set at or near the water table. Such dug pits may be as small as 4 ft. in diameter for vertical types of pumps. Where a pump and direct-connected motor are set in a dug pit, the size of the pit depends on the space required for the equipment. Rectangular or circular pits 10 to 12 ft. in size are typical of those used for direct-connected horizontal centrifugal pumping plants. Bored or drilled wells are used below the pit to penetrate the water-bearing material.

Wells used in irrigation are generally drilled (Fig. 103). Diameters vary from 10 to 20 in. under usual conditions. Where more than one well is used to supply a pump, or where only small yields can be secured, wells of less than 10 in. may be used. For the larger sizes of pumps which are set within the well casings, wells up to 24 or occasionally 30 in. in diameter may be used.

The depth of wells for irrigation varies with the formation and discharge desired. Usual depths are 60 to 300 ft. Shallow wells

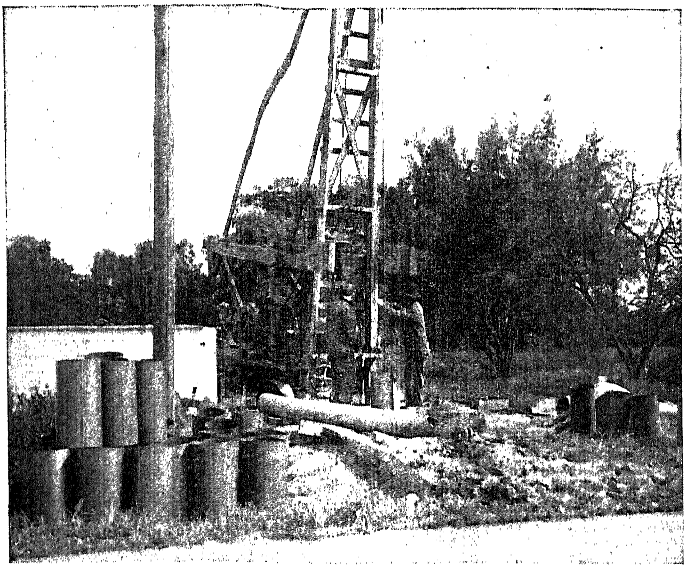


FIG. 103.—Well rig, sand bucket, and stovepipe casing. (*Courtesy of Bureau of Agricultural Engineering, U. S. Department of Agriculture.*)

may be used in open formations free from impervious strata. Where the water-bearing strata are separated by thick strata of tight material, it may be necessary to use wells several hundred feet in depth in order to secure an adequate water supply.

Well casing may be standard steel screw casing, single-riveted casing, or double-riveted casing of the California stovepipe type. The latter consists of two cylindrical casings, the smaller of which fits inside the larger. The sections are 2 to 4 ft. in length and are put together with broken joints. The casing is forced to follow the drill in the well by means of hydraulic jacks.

Where the location of the water-bearing strata and the final depth of the well are known, the casing can be made up as used,

so that the perforated portions come opposite the water-bearing strata. In much well drilling the desired location of the perforations is not known in advance and the casing is perforated in place. Various perforating tools are used, which generally give long narrow slit openings. The total area of the perforations should be large enough to permit ready inflow of water; it should be at least five times the cross-sectional area of the well in order to have low velocities and less loss of head through the perforations.

Wells are usually developed by pumping and surging so as to remove the finer sands from the material surrounding the casing and to permit more ready inflow. In materials containing coarse sand and gravel, considerable fine sand may be removed and the yield largely increased. Excessive sand removal may leave cavities around the casing and result in caving. In fine sands, the well may be drilled to a larger size than the casing and the space around the casing filled with fine gravel which acts as a strainer for the sand.

It is usual to land the casing in tight material when available. Where sufficient flow can be secured from one water stratum, the casing may be landed in clay above the water-bearing material and the well drilled through. This gives what is called an "open-bottom well" and avoids perforations. Combined perforated and open-bottom wells may also be used.

The discharge of wells should be developed before the permanent pumping equipment is installed. Development with temporary equipment enables the permanent pump to be selected in accordance with the results of pumping tests during development and avoids the wear caused by the sand pumped during the test period. While such development and testing of the well add somewhat to the cost, the better selection and saving in wear on the permanent installation will usually justify the additional expense.

Costs of well drilling vary with the size, depth, and formation. General costs applicable to California areas, free from cemented materials or boulders, are shown in Table XXIX. These costs are exclusive of the cost of the casing or its perforation. For less favorable conditions, drilling costs may be twice as high as the prices given in Table XXIX.

The cost of well casing depends on the size and thickness of metal used. For larger and deeper wells, 10-gage casing should

TABLE XXIX.—GENERAL COSTS OF WELL DRILLING PER FOOT FOR CALIFORNIA CONDITIONS

Diameter of well, inches	Depth of well				
	First 200 ft.	From 200 to 250 ft.	From 250 to 300 ft.	From 300 to 350 ft.	From 350 to 400 ft.
8	$1.00	$1.50	$2.00	$2.50	$3.00
10	1.25	1.75	2.25	2.75	3.25
12	1.50	2.00	2.50	3.00	3.50
14	1.50	2.00	2.50	3.00	3.50
16	2.00	2.50	3.00	3.50	4.00
18	2.50	3.00	3.50	4.00	4.50
20	2.50	3.00	3.50	4.00	4.50

be used; for smaller or more shallow wells, 14-gage may be sufficiently strong. For intermediate conditions, 12-gage is preferable. General costs of stovepipe casing applicable to California conditions are shown in Table XXX. A heavy starting section 10 to 15 ft. long is used on the bottom of the casing. A three-ply starter costs about twice as much per foot as the same size of double casing.

TABLE XXX.—GENERAL COSTS PER FOOT OF DOUBLE STOVEPIPE CASING FOR CALIFORNIA CONDITIONS

Diameter, inches	Gage of casing		
	14	12	10
8	$1.25	$1.50	$1.90
10	1.50	1.85	2.35
12	1.75	2.20	2.75
14	2.00	2.50	3.15
16	2.25	2.80	3.55
18	2.50	3.15	4.00
20	2.75	3.50	4.40

SELECTION OF THE SIZE OF PLANT

For the tighter formations, the maximum yield may be less than the desired capacity and the ground-water conditions will control the size of plant used. Where larger capacities can be obtained, there may be a choice of sizes of plants which may be used. In many areas, large enough yields may be secured so that

continuous operation is not required to meet the needs of the area to be served.

The service requirements of any pumping plant will depend on the area to be served and the factors which affect the rate at which water is used. The water requirements of crops have been discussed in Chaps. IV and V. The required capacity is determined by the period of maximum crop demand. For deep-rooted crops or for diversified areas, the demand may be distributed so that fairly steady operation may be secured.

Where yields in excess of the maximum requirements of service may be secured, a choice is offered between continuous and part-time operation. A smaller plant operated more nearly continuously will have a smaller first cost and, with electric power, lower average power costs. The supply obtained may be too small for efficient irrigation unless a reservoir is used to store the discharge for use in larger rates of flow. Such reservoirs also reduce the time of irrigation with a decrease in the cost of labor in applying water. A larger plant gives more flexibility in the adjustment of irrigation with other farm operations and each crop can be more quickly irrigated at its critical period of growth. Where ground-water conditions permit such choices in plant capacity, many installations are selected so as to operate from one-third to two-thirds of the time during the periods of main irrigation demand. For more expensive plants or high lifts where greater economy in operation is required, operation may be nearly continuous. Pumping 24 hr. a day nearly continuously for several months is frequently practiced by many of such California plants. On the other extreme are pumping plants supplying only supplemental irrigation, with occasional periods of operation. Plants of large enough capacity may be operated only during the daytime.

Reservoirs.—The economies of smaller plants continuously operated and the advantages of larger irrigation heads may be secured through the use of reservoirs. Such reservoirs usually have a capacity sufficient to hold 12- to 36-hr. discharge of the pumping plant. A capacity of 16-hr. pumping, so that irrigation can be limited to 8 hr. per day, is typical.

Such reservoirs are usually built by excavating the material for the banks from the area which is to form the reservoir. The banks have top widths of 2 to 3 ft. with side slopes of 1½ to 2 ft. horizontal for each foot of vertical height. The depth

of water stored is usually 4 to 6 ft. To store a discharge of 450 gal. per minute for 12 hr. would require a reservoir about 100 ft. square, holding water to a depth of 4 ft. The construction of such a reservoir without lining costs about $150. Larger reservoirs having an area of 1 acre cost about $400.00, where the value of the land used is $100.00 per acre and the cost of excavation $0.12 per cubic yard.

Where the soil is pervious, there may be considerable seepage from an earth reservoir. Such loss may be reduced by the use of puddled clay, oil, or concrete. For usual conditions, clay puddle or oil linings cost about 1 ct. per square foot, which about doubles the cost of unlined reservoirs. Concrete linings cost from 4 to 8 cts. per square foot, depending on the availability of the materials and the thickness of the lining used.

The economy of reservoirs depends largely on the form of the rate used for power. With high demand charges and low service rates there is a larger saving in power costs with a smaller plant operated more nearly continuously than would be the case with the form of power rates shown in Table XXXVIII. Reservoirs are not so generally used under such a form of rate as in former practice with larger demand charges per horsepower of connected load.

KINDS OF PUMPS

No one kind of pump is adapted to all of the varying conditions encountered in the use of ground water for irrigation. While there are a large variety of standard and special pumps available for such service, nearly all plants use one of the types of pumps described in the following pages. It is usually advisable for an individual owner to install one of the more generally used and thoroughly tried types of pump, leaving experiments with new types to those more thoroughly familiar with the operation of such equipment than is the usual irrigator.

CENTRIFUGAL PUMPS

This term is used for the ordinary type of centrifugal pump. It does not include deep-well turbines, although these operate on the centrifugal principle. Centrifugal pumps may be either horizontal or vertical, their classification on this basis depending on the position of the pump shaft instead of the plane of revolution of the vanes or runners.

A centrifugal pump consists of a circular casing with its inlet or suction end connected to the center, and its outlet or discharge end forming a tangent to the outer circumference. Inside the casing is the runner or impeller, which is keyed on the shaft and revolves with it. It consists of curved vanes closely fitting the casing. The revolution of the pump shaft and impeller imparts a centrifugal force to the water between the vanes which forces the water away from the center to the rim of the casing and into and through the discharge pipe. The outward flow of the water in the pump casing produces a partial vacuum at the center of the

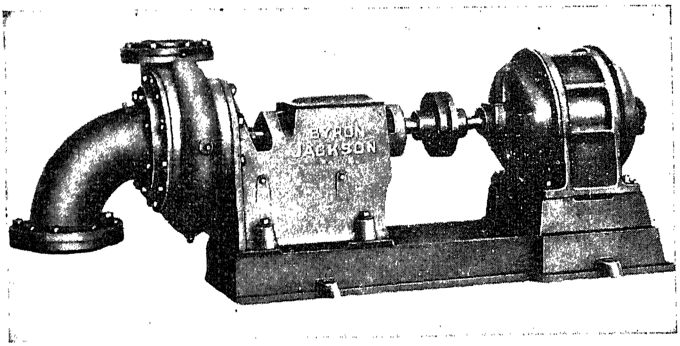


FIG. 104.—Horizontal centrifugal pump direct connected to motor. (*Courtesy of Byron Jackson Co.*)

impeller which causes water to flow into the casing, giving a continuous discharge. The discharge of a centrifugal pump is dependent on the speed, size, and form of the impeller and the lift or head against which the pump is working. For each pump there is a definite relationship between the speed of the pump, the lift, and the discharge. For each lift there is a speed at which the pump will operate most efficiently. The design of the impeller is based on both theory and experience. The manufacturers of centrifugal pumps will furnish ratings of their pumps. Purchase specifications designate the performance conditions to be met, leaving to the manufacturer the selection of the form and size of runner which will meet the performance requirements. Similar pumping results may be secured with larger runners of slower speed or with high-speed small impellers. Overspeeding is preferable to underspeeding, but any variation from the proper speed for the operating conditions reduces the efficiency of the pump.

Centrifugal pumps are both belt-driven and direct-connected to motors. Figure 104 represents a typical direct-connected horizontal centrifugal pump of a type frequently used for irrigation.

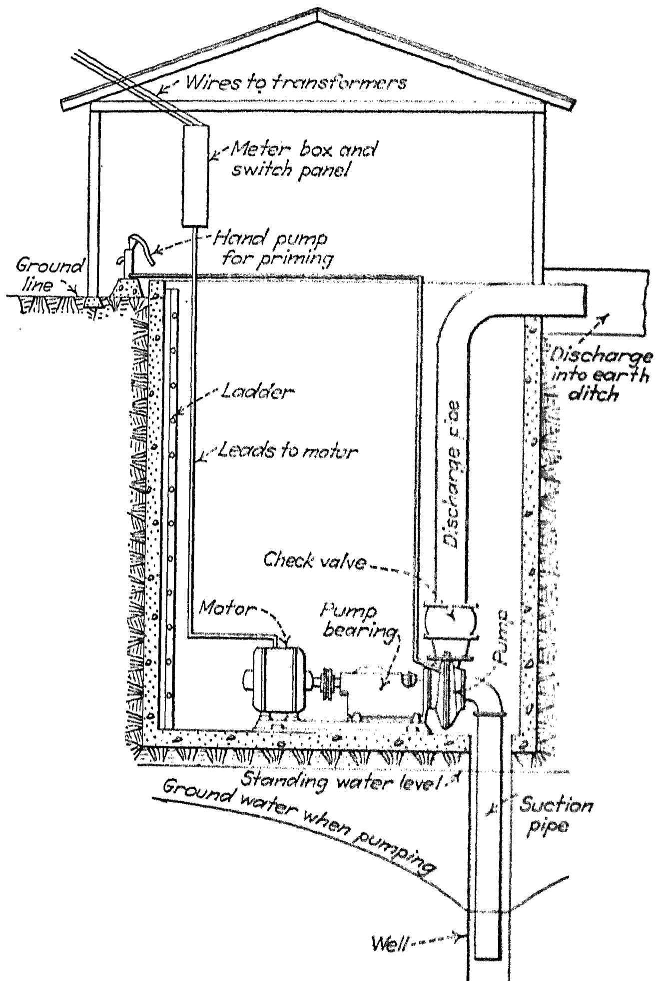


FIG. 105.—Section of direct-connected horizontal centrifugal pump in pit.

Figure 105 illustrates the installation of such a pump in a pit. The well extends below the pit into the water-bearing material.

To start a centrifugal pump, the suction pipe and the pump casing must be filled with water or primed. This may be done by

closing the discharge pipe with a check valve and connecting the suction end of a hand pump to the top of the casing. For small pumps and low lifts, a foot valve attached to the end of the suction pipe may be used and the pump primed by pouring water into the casing and suction pipe. If sand or other obstacles prevent tight closing of the foot valve, leakage through the valve may interfere with priming. Foot valves should not be used for lifts of over 40 ft. for sizes over 8 in. or for long discharge pipes, as the water hammer due to a sudden closing of the valve when the pump is stopped may split the shell of the pump.

While centrifugal pumps will operate under suction when primed for starting, it is advisable to keep the suction lift as small as may be practicable. While theoretically the pump will operate under suction lifts as great as 33 ft. at sea level and 30 ft. at an elevation of 3,000 ft., suction lifts in excess of 15 ft. result in decreased efficiency. It is necessary to operate horizontal centrifugal pumps under suction to avoid submerging the driving power. Vertical pumps may be more readily submerged and priming avoided. The smaller sizes of horizontal pumps of the grades used in irrigation are usually somewhat more efficient than vertical centrifugal pumps, owing to the shorter shaft and reduced difficulty of properly balancing the end thrust, but such advantages may be lost if horizontal pumps are operated under excessive suction.

Centrifugal pumps are designated commercially by the diameter of the discharge outlet in inches and the diameter of the runner; a 3 by 12 pump having a 3-in. outlet and a 12-in. runner. For the same diameter of outlet, the discharge varies with the size and design of the runner and the conditions of operation, so that capacities cannot be definitely stated for the different sizes. The general range of capacities for the centrifugal pumps used in irrigation is shown in Table XXXI.

Different types of centrifugal pumps are used for different classes of service. For pumping from wells with total lifts not exceeding 60 or 80 ft., the single-stage lower-speed stock type of pump of lower costs may be used. For higher lifts, such as pumping from open sources of water supply, higher-speed better-built single-stage pumps may be used for lifts up to or exceeding 200 ft. For the lower-head types of centrifugal pumps, the speeds for belt-connected pumps depend upon the capacity and lift. For small sizes of such pumps, speeds vary from 800 r.p.m. on low lifts to

TABLE XXXI.—CAPACITIES OF CENTRIFUGAL PUMPS IN GALLONS PER MINUTE

Size of pump	Minimum	Maximum	Usual
2	75	200	125
3	150	400	250
4	300	700	450
5	400	1,000	700
6	600	1,200	900
8	900	2,000	1,600

1,800 r.p.m. on lifts of 60 to 80 ft.; for larger sizes the speeds vary from 600 r.p.m. on low lifts to 1,000 r.p.m. on larger lifts. For motor-driven direct-connected pumps, speeds of 1,750 or 3,500 r.p.m. are typical of usual practice. For higher lifts, compound or multiple-stage centrifugal pumps can be used. These consist of two or more pumps connected in series on a single shaft with the

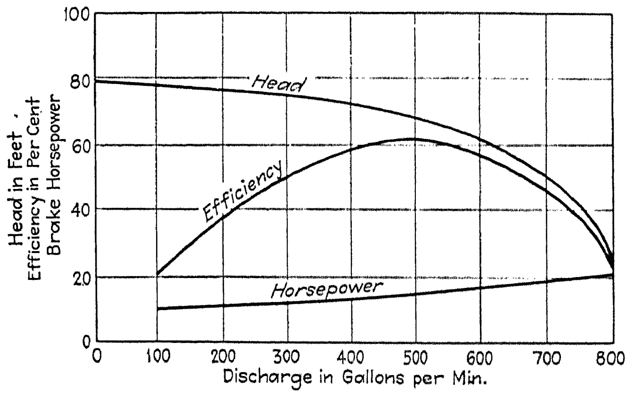


FIG. 106.—Typical characteristic curves for small low-lift centrifugal pump operating at a constant speed.

discharge of the first pump or stage delivered into the inlet of the succeeding stage. Multiple-stage centrifugal pumps are frequently used in other types of pumping but have a limited application in irrigation.

Typical discharge head or lift, over-all efficiency, and power relationships for a small centrifugal pump under favorable conditions of operation are shown in Fig. 106 for operation at a constant speed. The best efficiency is obtained at the head for which the pump is designed. When operated at the same speed, the pump will deliver water at both greater and lesser heads but at

a reduced efficiency. As the discharge delivered at the smaller heads increases more rapidly than the reduction in the head and efficiency, the power required increases as the discharge increases. By changing the speed to meet changes in head, more uniform efficiencies can be obtained over a wider range of discharge. By proper design of the runner, higher efficiencies at the designed head with more rapid decrease in efficiency with changes in head may be secured. Such runners are desirable when pumping under fixed lifts; for pumping from wells with the usual fluctuations in lift, the broader type of efficiency curves usually gives higher seasonal average efficiencies.

The efficiency shown in Fig. 106 represents the efficiency of the pump alone. Pumping plants for irrigation include inlet and outlet pipes with bends and valves. Power has to be supplied to overcome the frictional losses in the inlet and outlet lines of the pump as well as in the operation of the pump in raising water through the static lift. Different numerical values for the efficiency will be obtained, depending on the basis used for measuring the work accomplished. The pump manufacturer is responsible for the efficiency of the pump alone and, in many pump guarantees, the head against which the pump works is determined by the differences in pressure shown by gages at the inlet and outlet of the pump. Such efficiency for the pump alone will be numerically higher than the over-all efficiency of the entire plant. It is essential that the basis on which the efficiency is to be determined should be specified and understood in any pump guarantee. The power for driving the pump must be selected on the basis of the over-all efficiency. The losses of power in the inlet and outlet depend on the length and sizes of pipes used and the arrangement of valves. For usual conditions the over-all efficiency for small centrifugal pumping plants operating from wells will be about 5 per cent less than the efficiency of the pump alone.

The efficiency of a centrifugal pump depends on the conditions of operation as well as the design and construction of the pump. As shown in Fig. 106, the efficiency will vary with changes in the pumping lift. As the conditions of pumping from wells are frequently not uniform, the average seasonal efficiency of such pumps will usually be less than the efficiency of the pump under constant and favorable conditions. The guaranteed efficiencies both for the pump alone and for the over-all efficiency, which the

manufacturer can meet in an acceptance test, are higher than the owner can expect to maintain over a long period of operation.

The efficiency of centrifugal pumps varies with the size. For pumps selected to meet the conditions of operation and with properly selected inlets and outlets, the continuous-operation over-all efficiencies shown in Table XXXII should be obtained. These efficiencies are based on the power delivered to the pump and the water lifted through the static head.

TABLE XXXII.—OVER-ALL EFFICIENCIES THAT SHOULD BE OBTAINED UNDER CONTINUED OPERATION OF SINGLE-STAGE CENTRIFUGAL PUMPS

Based on power delivered to pump and static lift

Size of pump	Usual capacity, gallons per minute	Efficiency, per cent
2	125	35
3	250	45
4	450	50
5	700	50
6	900	55
8	1,600	55

Tests of large numbers of centrifugal pumping plants under field conditions show smaller average over-all efficiencies than those shown in Table XXXII. This is due to the inclusion in the average of many plants poorly selected in relation to the operating conditions, improper speeding in relation to the lift, particularly where ground-water levels have fluctuated, and excessive losses in inlets and outlets. A well-selected and maintained plant with an average grade of equipment should maintain the efficiencies shown in Table XXXII. Higher-grade equipment under favorable conditions of operation will show somewhat higher efficiencies.

Approximate factory costs of centrifugal pumps are shown in Table XXXIII. Costs of centrifugal pumps vary with the type of inlet and casing and character of workmanship. The cost figures in Table XXXIII are not a definite guide to costs in individual installations but furnish a general comparison of the relative cost of different sizes and types.

The costs for belt connection include the coupling and pulley; those for direct connection are complete except for the driving motor. The larger cost of belt-connected pumps is due to the higher speed usual with direct-connected pumps and the larger

TABLE XXXIII.—APPROXIMATE COSTS OF SINGLE-STAGE CENTRIFUGAL PUMPS

Size of pump	Usual capacity, gallons per minute	Cost for less expensive pumps for lifts up to 80 ft.		Cost for higher-speed medium-grade pumps, lifts up to 150 ft.	
		Belt connection	Direct connection	Belt connection	Direct connection
2	125	$ 45	$ 65	$ 65	$125
3	250	60	85	90	175
4	450	80	120	110	200
5	700	100	135	125	250
6	900	125	150	170	325
8	1,600	180	250	225	460

bed plate required. The cost of two-stage centrifugal pumps is about four times that of single-stage pumps of similar capacity.

Centrifugal pumps are used for lifts of 30 to 40 ft. from wells, the pump being set within suction limit of the ground water. The pit is frequently carried to the ground water with the pump placed at or near the ground water level, the drawdown becoming the suction lift. Horizontal centrifugal pumps were formerly used directly connected to motors in pits up to 40 or 50 ft. in depth. Vertical centrifugal pumps connected to the driving power at the ground surface by a long vertical shaft were also used with pits up to 75 or occasionally 100 ft. in depth. Both of these deeper-pit types of installation have been largely replaced for new installations by deep-well turbine plants. Where the ground water is subject to a considerable range of fluctuation, resulting in either submergence of the pit or excessive suction, deep-well turbines are now being used in preference to centrifugals for average depths to ground water as low as 25 or 30 ft. For conditions to which it is adapted, the centrifugal pump will furnish the capacity of the well at lower first costs and operating costs with the minimum of mechanical complications. Centrifugal pumps are also extensively used for pumping from surface sources of water supply.

DEEP-WELL TURBINES

This term is used to designate a type of centrifugal pump adapted to operate within the limited space conditions of the well

casing. This makes it necessary to use small-diameter impellers, or "bowls" as they are generally called, which reduce the amount of lift obtainable from each stage. The impellers may be of either the open or closed type (Fig. 107). The lower impellers in Fig. 107 are of the centrifugal type; the upper represent mixed-flow impellers. A separate stage or bowl is generally used for each 15 to 30 ft. of lift, so that deep-well turbine pumps are nearly always multiple-stage units. The pump is suspended in the well from a pump head, at the ground surface, the driving power being

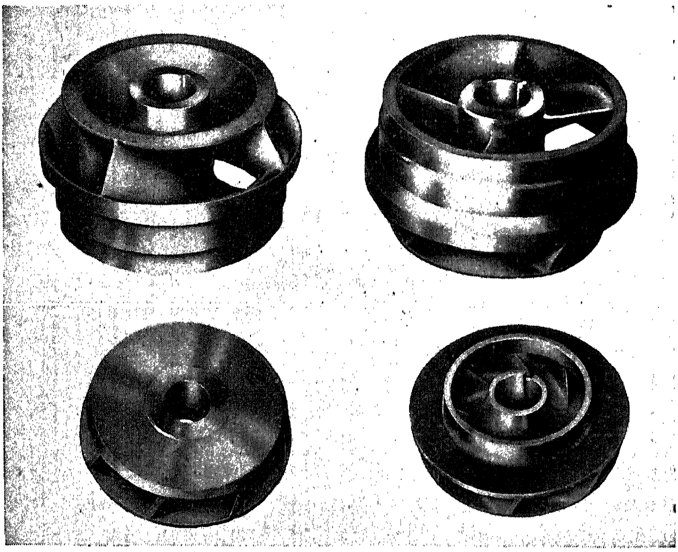


FIG. 107.—Types of impellers for deep-well turbine pumps. (*Courtesy of Peerless Pump Co.*)

transmitted to the pump through a vertical shaft. The pump head includes the connections for the driving power and the bearings which carry the weight of the pump. The pump column, which includes the driving shaft and discharge pipe, is usually built in 10-ft. sections. The discharge pipe surrounds the driving shaft. The shaft is separated from the discharge pipe by an enclosing pipe, the space between the shaft and the enclosing pipe being filled with oil or water for lubrication. Deep-well turbines are submerged in the well so that provisions for priming are not required. A cut-away view of a deep-well turbine installation with a built-in direct-connected motor is shown in Fig. 108.

The pump head may be built for belt connection or for direct connection to a vertical motor. For direct connection, the pump shaft and motor shaft may be connected by means of a flexible coupling, or the pump shaft may be extended to form the motor shaft, the motor being built into the pump head. The latter method is now generally used.

A strainer is desirable on the bottom of the inlet pipe of the pump to prevent materials entering the runners which may interfere with their operations. Such a strainer should have small enough openings to prevent the entry of any materials which cannot pass through the runners. The strainer should have a total area of opening equal to four to five times the cross-sectional area of the inlet pipe.

In order to have space for the pump, somewhat larger wells are generally used for deep-well turbine plants than for ordinary centrifugal pumps. The size of the deep-well turbine is designated by the diameter in inches of the well in which it may be used. A No. 12 deep-well turbine may be used in a 12-in. well; the clearance of the outside of the pump is from ½ to 1 in. Deep-well turbines for domestic use are made for use in wells as small as 4 in.; for irrigation, usual minimum sizes are 8 or 10 in. and usual maximum 20 to 24 in. with occasional wells as large as 30 in. Where the well is drilled to much depth below the setting of the pump in order to penetrate adequate water-bearing strata, the diameter of the lower portions of the well may be less than that used above the pump. Where future ground-water lowering may occur, the larger diameter of the well should be used to as great a depth as it is anticipated the pump may need to be lowered.

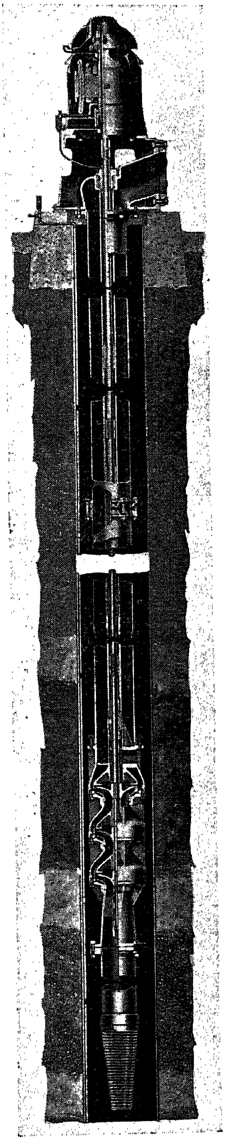


FIG. 108.—Sectional view of deep-well turbine pumping plant. (*Courtesy of Sterling Pump Corp.*)

The capacity of deep-well turbine pumps varies with the size, speed, and form of runner.

Table XXXIV illustrates the usual range of capacity for different sizes of wells.

TABLE XXXIV.—CAPACITIES OF DEEP-WELL TURBINE PUMPS

Diameter of well, inches	Capacity of deep-well turbine pumps, gallons per minute	
	Usual minimum	Usual maximum
4	20	70
6	50	200
7	100	300
8	150	500
10	250	800
12	400	1,200
14	500	1,500
16	700	1,800
18	1,000	3,000
20	1,500	3,500
24	2,000	5,000

Efficiencies of deep-well turbines are expressed in terms of the power required and the total static lift from the water level in the well when pumping to the point of delivery. The power may be based on the power delivered to the pump shaft or for motor-driven direct-connected plants it may be the power at the meter on the inlet side of the motor. In the latter case the efficiency includes the loss of power in the motor. It is not practicable to determine the efficiency of deep-well turbines separately from the inlet and outlet losses as may be done in the case of centrifugal pumps.

The efficiency of deep-well turbine plants varies with the capacity and lifts. For power delivered to the pump shaft, efficiencies similar to those shown in Table XXXV should be obtained for all-season operation under usual conditions. With constant lift, well-selected plants may exceed these efficiencies. For the usual fluctuations in lift and care in maintenance, these efficiencies should be secured. Many plants operate at lower average efficiencies.

The cost of deep-well turbine pumps varies with the size of the well and the lift. The purchase of the pump includes the pump, columns, and power head. The cost exceeds that of centrifugal

pumps of similar capacity. Owing to the number of variable factors involved, it is not practicable to prepare a simple tabulation covering costs. Table XXXVI presents a few typical factory costs for California conditions in 1932.

TABLE XXXV.—OVER-ALL EFFICIENCIES THAT SHOULD BE OBTAINED UNDER CONTINUED OPERATION OF DEEP-WELL TURBINE PUMPING PLANTS

Based on power delivered to pump shaft and static lift

Capacity of Pump, Gallons per Minute	Efficiency, Per Cent
100	35
200	45
300	50
500	55
1,000	55
1,500	60
2,500	60

TABLE XXXVI.—APPROXIMATE COSTS OF TYPICAL DEEP-WELL TURBINE PUMPS FOR 100-FT. LIFTS

Discharge, gallons per minute	Direct-connected unit, including motor	Belted head, without motor
225	$ 900	$ 775
450	1,050	875
900	1,400	1,175

For 50-ft. lifts the corresponding costs would be from 60 to 75 per cent of the costs for 100-ft. lifts. For 150-ft. lifts the corresponding costs would be from 120 to 160 per cent of those for 100-ft. lifts.

A typical characteristic curve for a deep-well turbine pump for a single speed is shown in Fig. 109. The form of such curves can be varied by the design of the impeller. The efficiency shown in Fig. 109 is fairly well maintained over a considerable range of discharge. The discharge delivered by such a pump operating at a constant speed increases as the lift decreases. The brake horsepower for the pump shown in Fig. 109 increases somewhat with the increase in discharge, as the changes in efficiency and lift are not sufficient to counterbalance the change in discharge. The

impeller may be designed so that the discharge does not increase so rapidly with reductions in lift and thus an increase in the brake horsepower required at lower lifts may be avoided. Such impellers are known as having non-overloading runners. This is an advantage where motors are used, as overloading with possible heating is avoided. Runners may also be designed with a higher

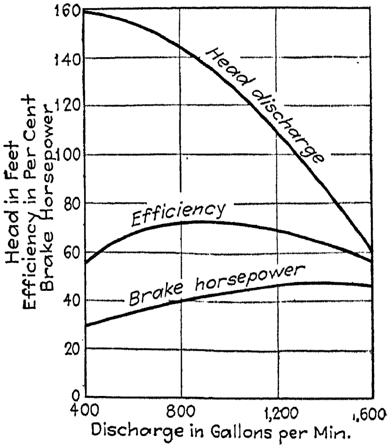


FIG. 109.—Typical characteristic curves for deep-well turbine pump operating at a constant speed.

efficiency over a narrower range of discharge, with more rapid decreases in efficiency under both larger and smaller lifts. For general irrigation use from wells where fluctuations in lift frequently occur, runners with the flatter efficiency curves will usually give higher average efficiencies for all-season operation.

Deep-well turbine pumps now represent the most extensively used type for plants pumping from ground water. When first introduced, their use was generally limited to conditions of large discharge and higher lift for which other types were less adapted. With improvements in the efficiency and dependability of operation, deep-well turbines have largely invaded the field of the deep-well plunger pump and have narrowed that of the ordinary centrifugals to lower lifts than were formerly used. While the first cost of installation is higher than for centrifugal pumps, the ability to avoid priming by submergence, the ease of adjustment to lowering ground water by adding bowls and extending the

pump column, and the infrequent removal from the well required for repairs have caused this type of plant to be extensively used in recent years. Nearly all pump manufacturers attempting to serve the irrigation field now make deep-well turbine pumps either as a single line or together with other types. Deep-well turbines are now used for lifts of over 300 ft. Water may be pumped to elevations above the ground level at the well by using sufficient stages to furnish the necessary pressure, although most plants discharge the water pumped at or near the ground level at the pump.

POWER PLUNGER PUMPS

This term is used for piston or plunger pumps of the ordinary types used for pumping from sources of water supply near the

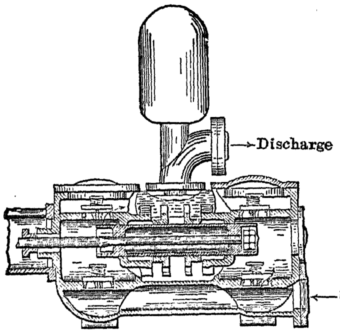


Fig. 110.—Double-acting cylinder of plunger pump.

surface, usually where the operating lift is large. Pumps of this type used for irrigation do not differ from those used under similar conditions for other purposes, such as municipal supply. The pump consists of one or more cylinders; in each cylinder a piston, moving backward and forward, draws the water into the cylinder and forces it into the discharge pipe. When there are only one suction and one discharge valve on each cylinder, the pump is called "single acting," as the piston moving in one direction fills the cylinder by suction and moving in the other direction discharges the water so drawn in. When the cylinders have two sets of inlet and outlet valves so that there is a filling and discharge of the water alternately on opposite sides of the piston at

each stroke, it is called "double acting." Pumps with two cylinders are called "duplex," and those with three cylinders "triplex," pumps; in either type the cylinders may be single or double acting. Double-acting or multiple-cylinder pumps give a more steady discharge with less pulsation than single-acting single-cylinder types. Power plunger pumps are self-priming by pumping out the contained air. A double-acting single-cylinder pump is shown in Fig. 110.

The capacity of plunger pumps depends on the volume of the strokes and the speed of the pump. The full capacity of the pump may not be obtained owing to slippage past the piston. For pumps in good condition such slippage should not exceed 3 or 4 per cent. For worn packing or loose pistons it may exceed 10 per cent on high pressures. The capacity without slippage for typical sizes operated at usual speeds is given in Table XXXVII. Some pumps designed to operate at higher speeds have larger capacities than those given in Table XXXVII.

Table XXXVII.—Capacities of Typical Power Plunger Pumps

Diameter of water cylinder, inches	Length of stroke, inches	Revolutions or strokes per minute	Discharge, U. S. gallons per minute
Double-acting single-cylinder pumps			
6	8	35	69
8	8	35	122
Single-acting triplex pumps			
4	6	40	39
5	8	35	71
6	10	35	129
7	10	35	175
8	10	35	228
Double-acting duplex pumps			
4	6	40	52
6	8	35	138
8	10	35	304
9	10	35	385

The efficiency of power plunger pumps varies with the size of the pump and the lift. The losses of power in friction are rela-

tively smaller for larger sizes and lifts. For smaller sizes having capacities of 50 gal. per minute, over-all efficiencies varying from 35 per cent for 50-ft. lifts to 65 per cent for 200-ft. lifts should be obtained. For plants of 300 gal. per minute capacity, the efficiency varies from 50 to 75 per cent for lifts of 50 to 200 ft.

Plunger pumps have a higher cost for moderate lifts for a given capacity than centrifugal pumps. For higher heads, for which multiple-stage centrifugal pumps would be required, plunger pumps may have lower costs than centrifugal pumps.

Plunger pumps for irrigation are used for large lifts where water is secured from surface sources. Such sources may be streams or reservoirs into which water from wells is pumped. Plunger pumps have a relatively high efficiency and are dependable in operation. For the larger capacities of such booster service or for lifts sufficiently low to be handled with single-stage pumps, centrifugal pumps are more generally used.

Deep-well Plunger Pumps.—The action of these pumps is similar to that of other power plunger pumps but, like the deep-well turbines, the deep-well plunger pumps are adapted to the operating and space conditions of the well casings. Deep-well plunger pumps usually consist of the equivalent of two single-acting cylinders placed end to end, the discharge of the lower cylinder passing through the upper. The lower plunger is connected to a solid rod which fits into a hollow rod to which the upper piston is connected. The plungers are operated by the driving power at the ground surface so that the two cylinders give a continuous discharge, one plunger moving up while the other moves down. The driving power is transmitted to the pump rods through various forms of gears or cams. All working strokes are on the upward movement of the plungers with the driving rods or shaft under tension, the downward or compression strokes being the idling stroke. The cylinder is set low enough to be self-priming.

Above the cylinder is the vertical discharge or column pipe into which the cylinder delivers its discharge for conveyance to the point of discharge. The size of the cylinders varies from as small as 3 in. in diameter with a 20-in. stroke to 16-in. diameter and 36-in. stroke. The speed varies from 15 to 35 strokes per minute.

The valves are within and concentric with the plungers. To avoid frequent removal of the pump for renewal of the piston packing, pistons several inches thick with multiple packing are

used. Such pistons also enable the valves to be placed in them more effectively than for shorter pistons.

Deep-well plunger pumps have been used on lifts of over 300 ft. The capacities are generally less than 400 gal. per minute but pumps having capacities as large as 1,000 gal. have been used. Deep-well plunger pumps of the sizes used for irrigation with the packings in good condition should have over-all efficiencies, based on the power delivered to the pump head, varying from 50 to 65 per cent, the higher efficiencies being secured with the larger lifts and capacities.

For high lifts and small discharges, deep-well plunger pumps have a somewhat higher efficiency than other pumps available for similar conditions. The first cost of such plunger pumps is higher than that for other pumps of the same capacity.

Deep-well plunger pumps were formerly quite generally used for pumping from wells with high lifts for discharges of about 250 gal. per minute or less. The development of smaller sizes of deep-well turbines has resulted in the general use of turbines for such pumping conditions, so that few new deep-well plunger pumps are being installed for irrigation, although many of such pumps are still in use.

AIR-LIFT PUMPS

Air-lift pumps operate by delivering sufficient compressed air into the water in a well far enough below the standing water level so that the lighter mixture of air and water in the well is forced upward above the point of discharge by the weight of the air-free water surrounding the well. If the air-discharge pipe is submerged to a depth equal to the lift and sufficient air discharged to result in a mixture of over one-half air and less than one-half water in the well, the column of mixed air and water will rise to the height of the lift to balance the weight of water surrounding the well. The air pressure and the amount of air required vary with the depth of submergence. The depth of submergence should be equal to the lift for efficient operation.

An air-lift plant consists of (1) the water-discharge pipe which is smaller than the diameter of the well and is placed inside the well casing to the depth of submergence to be used; (2) a smaller air pipe to deliver the air into the water which may be placed either inside or outside the discharge pipe; (3) a foot piece which consists of a casting connected to the lower end of the air pipe and

is designed to discharge the air into the water evenly and in small bubbles; (4) the tailpiece which is a slightly enlarged extension of the lower end of the discharge pipe below the foot piece.

The air compressor may be driven by any available form of power. The compressed air passes through an air receiver which is used to store the air and equalize the pressure. The efficiency of a properly installed compressed-air plant as calculated from the ratio of actual pumping accomplished to the horsepower developed in the motive power of the compressor is generally from 20 to 30 per cent.

Air-lift pumps are adapted for use where the yield of single wells is less than the discharge desired and a battery of wells is required. A central compressor plant with air lines to each well may be as economical as separate power units and pumps on each well. Air lifts are also adapted for use in wells which have been deflected in drilling, so that shaft types of deep-well pumps cannot be used owing to the crookedness of the casings; the air lift may enable the well to be used, the value of the salvage on the well balancing the lower efficiency of the air lift. Air lifts are also used for cleaning out sand and developing new wells. For such temporary use, the higher costs of operation due to the low efficiency are more than balanced by the simplicity of installation.

OTHER TYPES OF PUMPS

Other types of pumps less extensively used in irrigation include rotary and screw pumps, scoop wheels, and hydraulic rams.

Rotary pumps are displacement pumps having rotating elements. The pumping action may be secured by the use of cams, screws, gears, or vanes. Such pumps are not adapted for use in wells but are used in the smaller sizes for some pumping from open-water supplies.

Screw pumps are of the propeller type. These vary from large-capacity low-head plants pumping from open-water surface supplies to propellers distributed at intervals of 4 to 6 ft. along a shaft for pumping from wells. Vertical screw-type pumps of the first type are now used for lifts up to 30 ft. Some propeller types of well pumps are used in small wells and occasionally in larger sizes. For wells up to 4 or 6 in. in diameter, a propeller pump can secure larger discharges than deep-well turbines, as there is less restriction in flow in the limited area of the well. For larger

sizes of well, deep-well turbines have very largely replaced the use of propeller pumps.

Scoop or paddle wheels may be used for pumping in ditches for lifts up to 6 or 8 ft. When properly designed, such pumps may have higher efficiencies than are obtainable with other types of pumps on such low lifts. Such pumps may be used to lift water from ditches to higher lands on the farm where only a few feet of lift is required.

Hydraulic rams are used for lifting water where water is available under pressure to furnish the power required. Pumping action is obtained by checking of the momentum of the power water to create pressures under which a part of the flow may be delivered at higher levels. Rams are not applicable to pumping from wells. They are frequently used for domestic pumping but have very limited application in irrigation.

FACTORS AFFECTING THE EFFICIENCY OF PUMPING PLANTS

The efficiencies of pumping plants vary widely with the type of plant and the care given to its operation. For usual field conditions, irrigation pumping plants properly selected, installed, and maintained should obtain the efficiencies that have been stated for the different types of pumps. Tests made on a large number of pumping plants under field conditions show that the average efficiency of any group of similar size and type of plants is much less than the efficiency that should be obtained. Poor selection of the pump for its conditions of use, incorrect speeding, poor maintenance, excessive loss in friction in pipes or valves, or other factors usually result in much more loss of efficiency than differences in the design or workmanship of different makes of pumps.

The pump manufacturer is responsible only for the performance of the equipment which he supplies. As previously described for centrifugal pumps, the guaranteed efficiency may be that of the pump alone; for deep-well turbines the over-all efficiency for the inlets and outlets as well as the pump is used. As the turbine manufacturer also furnishes the inlet and outlet column, the efficiency guarantee for such pumps covers the part of the installation for which the manufacturer is responsible. Over-all efficiencies based on the static lift are about 5 per cent lower than the efficiency of the pump alone.

Seasonal efficiencies are lower than those obtained under acceptance tests. In addition to any losses in efficiency due to

wear on the equipment, fluctuations in ground-water elevation affect the efficiency unless the speed of operation can be adjusted to the change in lift. Some ground-water fluctuation usually occurs and is frequently sufficient to be a factor in the efficiency.

Friction losses in inlets and outlets may be reduced by using larger sizes and avoiding sharp bends. The diameter of the suction and outlet pipes should be 1½ times that of the pump inlet and outlet for centrifugal pumps. Where surface-water supplies are used, strainers should be used to avoid drawing trash into the pump and the inlet should be designed so that sand does not enter. The area of such strainers should be large enough to avoid loss of head through the strainer. The discharge of the pump should be at as low an elevation as the conditions of use will permit.

While pumps may be purchased on the basis of the efficiency of the pump alone, in estimating the size of driving power and power consumption, the over-all efficiency should be used. Costs of pumping depend upon such over-all efficiencies.

METHODS OF DRIVING IRRIGATION PUMPS

The driving power for irrigation pumps is usually either an electric motor or an internal-combustion engine. For larger plants or in isolated locations, steam may be used. Where electric power is available, it is generally used for plants operated to a sufficient extent to obtain a low average cost of power. Some of the various types of gas engines are frequently used where electricity is not available, or for irregular operation.. These include engines adapted to use all of the various grades of fuel from crude oil to gasoline. Natural gas, when available, is also used for irrigation pumping.

Motors used for irrigation pumping are selected from the standard forms of motors used for other purposes. The performance and efficiency of motors are generally definite and uniform. Larger variations occur in the performance of engines, depending on their design and workmanship as well as the care used in their maintenance and operation. For infrequent operation, low first cost becomes relatively more important than fuel economy and cheaper-grade equipment may show better total economy. For short-period operation, tractor engines, made-over automobile engines, or similar power units may be used. For more nearly continuous use, better-grade equipment should be used.

For such use, gasoline engines selected for the character of load are used up to 20-hp. sizes, and oil engines using cheaper types of fuel in sizes larger than 20 hp. Semi-Diesel and Diesel types of engine are available in sizes of about 40 hp. or larger. Such engines are economical where operated by those experienced in their use.

The connection between the driving power and the pump may be direct or by means of belts, gears, or chains. Centrifugal types of pumps operate at speeds similar to those used for motors. For motor-driven centrifugal or deep-well turbine pumps, direct connection is generally used unless it is desired to vary the speed ratio owing to fluctuations in the lift. Direct connection is preferable where applicable, as the loss of power in transmission is avoided and the unit is more compact. For direct connection, centrifugal types of pumps are designed to operate at speeds used in standard motors. For such use it is essential that the pump be operated with a motor having a speed equal to that for which the pump is designed. The direct connection is usually made through a flexible shaft coupling. While two-speed motors may be used, direct-connected pumps are generally operated at a constant speed.

Belts are generally used for indirect connection. By proper selection of the size of pulleys, any desired speed ratios may be secured. The driving shafts of the power units are usually horizontal. For pumps with horizontal shafts, direct belt connections with short belts may be used. For vertical-shaft pumps, belts with quarter turns are required; distances between shafts of 20 to 25 ft. are needed and, unless the belt is properly adjusted, idlers may be needed to hold the belt on the vertical pulley. Gears and chains are not generally used in irrigation pumping; the speed of centrifugal types of pumps is usually too high for best results with these methods.

Power Requirements.—The power required to lift water is expressed in horsepower or kilowatts. One horsepower represents the energy required to lift 33,000 lb. through a height of 1 ft. in 1 min.; this in turn is equivalent to raising 3,960 gal. of water through a height of 1 ft. in 1 min. A kilowatt equals 1⅓ hp. or more exactly 1 hp. equals 746 watts. The net horsepower or the horsepower with 100 per cent efficiency required in any given case is equal to the discharge of the pump in gallons per minute, multiplied by the total lift in feet and divided by 3,960.

Most pumps are rated in terms of gallons per minute; for conversion to second-feet, 450 gal. per minute is used as equal to 1 sec.-ft. The horsepower delivered by an engine or motor is called the "brake horsepower." The brake horsepower is delivered to the pump with direct-connected units and less belt losses with belt connection. Losses of energy in belt connection vary from 5 to 15 per cent of the brake horsepower under usual irrigation conditions. The brake horsepower delivered to a pump must exceed the net or useful work accomplished by the pump by the amount of the energy losses in pumping. The ratio of input power to useful output represents the efficiency of the pumping operation. Engines and motors are rated commercially in terms of the brake horsepower. With electric power, the rate at which power is registered on the electric meter exceeds the brake horsepower owing to losses of energy in the motor, as the meter is on the inlet side of the motor.

To lift 1 acre-foot of water through a height of 1 ft. would require 1.375 hp.-hr. or 1.025 kw.-hr. at 100 per cent efficiency. For 50 per cent efficiency, twice these amounts of power would be required for each acre-foot lifted 1 ft. The power required for any other efficiency can be obtained by dividing the power required with 100 per cent efficiency by the ratio of the actual efficiency to 100.

POWER CONSUMPTION AND COST

Power consumption for internal-combustion engines is expressed in terms of the amount of fuel used per brake horsepower hour. While engines in good condition will deliver a brake horsepower hour on a fuel consumption of $\frac{1}{8}$ gal., average use for the season is more usually about $\frac{1}{6}$ gal. per brake horsepower hour. The type of fuel used varies with the character of engine. The semi-Diesel or Diesel engines use cruder forms of oil of lower cost. While gasoline is sometimes used for irrigation pumping, the less fully refined products are more usual. The cost of the fuels used with engines varies widely with the type of fuel and location of the pumping plants in relation to fuel supplies.

Electrical energy is measured in kilowatt-hours. The electricity used is metered between the transformers and the motor and the power measured and charged for includes the loss of power in the motor as well as the brake horsepower delivered to the pump. The efficiency of the motors used in irrigation pumping varies

from about 85 per cent for the smaller sizes to 90 per cent for the larger capacities. One kilowatt of electrical energy delivered to the motor will produce 1.13 and 1.20 brake horsepower with 85 and 90 per cent motor efficiencies, respectively, or 1 brake horsepower requires 0.87 and 0.83 kw. at the meter for the same motor efficiencies.

Cost of Electric Power.—Different forms and amounts of rates for electric power for pumping are charged by companies serving different areas. A power company must always have a sufficient amount of power available to meet the maximum load that may come on its system at any time. It is more expensive to serve a load that may have a high peak demand and a short period of use than a load which uses more kilowatt-hours but has a smaller peak. Nearly all power rates for irrigation pumping now consist of two parts: one, a demand charge based on the maximum rate of use of power, and the other a service charge, based on the kilowatt-hours used per kilowatt or horsepower of demand. The price per kilowatt-hour is frequently on a sliding scale, becoming less for larger amounts of use per unit of connected load.

TABLE XXXVIII.—TYPICAL RATE SCHEDULE FOR AGRICULTURAL POWER FOR CALIFORNIA CONDITIONS

Load, horsepower	Demand charge per year per horsepower	Service charge, cents per kilowatt-hour for power used per horsepower of load			
		First 1,000 kw.-hr., cents	Second 1,000 kw.-hr., cents	Third 1,000 kw.-hr., cents	All over 3 000 kw.-hr., cents
1 to 4........	$6.50	1.5	0.8	0.7	0.6
5 to 14.......	5.50	1.3	0.8	0.7	0.6
15 to 49......	5.00	1.25	0.8	0.7	0.6
50 to 99......	4.50	1.2	0.8	0.7	0.6
Over 100.....	4.00	1.15	0.8	0.7	0.6

A typical California rate for electric power for agricultural use is shown in Table XXXVIII. The year begins Apr. 1. Contracts covering payment of the demand charge for 3 years have been required by some companies as a condition for supplying service.

Other rates, as used in some of the other states, include schedules based on the kilowatt-hours used per horsepower of load per

month with sliding scales varying from about 5 cts. for the first block to 2 cts. for the excess use with a minimum charge per horsepower per year.

As indicated by the preceding illustrations of the forms of rates, the average cost per kilowatt-hour for electric power depends largely on the proportion of the time the plant is operated. For the rate shown in Table XXXVIII, the average price per kilowatt-hour including the demand charges varies from 2 cts. per kilowatt-hour for operation for 10 per cent of the time per year to 1 ct. per kilowatt-hour for operation for one-half of the time per year. Rates in other areas vary widely, depending on the conditions of service and use. In the mountain states the pumping season is short and the consumption per horsepower of connected load is relatively small. In such areas the price per kilowatt-hour may be high but the total cost per acre may not be large. Some power companies have relatively low rates on the use of surplus power which may be available for irrigation pumping during the summer season.

FIXED CHARGES

Fixed charges represent the costs which are charged against a pumping plant in addition to the direct power and operation expenses. These include interest on the first cost, taxes, depreciation, and repairs.

When money is spent on the installation of a pumping plant, the cost of the use of the plant includes interest and provision for the replacement of the plant when it becomes worn out. Interest rates vary with the character of the security; for usual conditions 6 per cent is representative of the rate at which capital may be obtained for such plants. The period of useful life of the different parts of the plant varies. Wells should last 10 to 20 years; many wells last much longer before corrosion of the well casing requires their replacement. Shorter lives may be obtained where caving or other mechanical injury occurs. Pumps may be used for periods of 12 to 20 years under usual conditions. Motors should have useful lives of 15 to 20 years, engines from 10 to 15 years for the conditions of use encountered in pumping for irrigation. For general conditions, the resulting average depreciation to provide for replacement when required is about 4 per cent per year on a sinking-fund basis with interest at 6 per cent.

Repairs will be required on engines, motors, and pumps. These vary from minor items, as needed, to general overhauling at occasional periods. The annual costs of repairs and maintenance on pumping equipment average from 1 to 3 per cent of the first cost. Wells may need cleaning if sand enters when pumping. Such costs are widely variable.

Taxes vary with the tax rate and basis of valuation. Taxes may represent from ½ to 1½ per cent of the first cost of the plant. In some areas, assessed values are based on the value of the pumping plant separately from the assessed value of the land on which the water pumped is used. For such conditions, the taxes become a direct charge against the pumping.

For general conditions, average fixed charges may be taken as follows:

	Per Cent
Interest	6
Depreciation	4
Repairs	2
Taxes	1
Total	13

Fixed charges may be somewhat higher on engine plants than on motor-driven pumps owing to the shorter usual life of the engine and the larger amount of repairs generally required.

Attendance.—The cost of attendance for a small pumping plant is difficult to segregate from other costs of irrigation. For plants serving a single farm, the irrigator usually attends to both the pump and the distribution of water in the field. As any time spent with the pump reduces the time that can be spent with the water in the field, it is proper to charge the pump with the time so used, although no additional expenditure may be actually incurred. Both electric and engine plants have been improved so as to operate with less attendance than was formerly required and the attendance cost should not be large. Starting and other attention requires more time with engines than with motors. A charge of $0.50 to $1.00 per day for attendance would represent usual costs for 24 hr. per day operation with small plants. For daytime operation only, the costs would be about two-thirds of the 24-hr. costs.

COSTS OF PUMPING PLANTS

Costs of the more generally used pumps have been discussed with the description of the types of pumps. While such costs vary with the grade of the equipment, distance from point of manufacture, and general price levels, the costs stated indicate the general relationships of costs for the different types and of different sizes of the same type. No pumping plant should be constructed without securing local quotations at the time of construction, determining the cost of delivery of pumped water, and balancing such costs against the value of the use of the water to be obtained before the cost for the plant is actually incurred.

Approximate costs of typical power equipment used in irrigation pumping is illustrated in Table XXXIX.

TABLE XXXIX.—GENERAL COSTS FOR MOTORS AND ENGINES FOR IRRIGATION PUMPING

Horsepower of motor or engine	Cost of electric motors, 1,200 r.p.m.	Cost of gasoline engines	Cost of oil engines	Cost of semi-Diesel engines
2	$ 70	$ 70		
3	85	115		
5	110	135		
$7\frac{1}{2}$	200	210		
10	220	400	$ 750	
15	255	500	950	
20	300	800	1,200	
25	325	....	1,500	
30	375	....	2,000	
40	475	....	......	$2,600
50	525	....	......	3,100

Higher-speed motors have lower costs. Few semi-Diesel types of engines have been used in irrigation in sizes smaller than 40 hp. For smaller plants, power may be obtained from tractors or other temporary sources. In the smaller sizes the cost of motors and engines is similar; in larger units motors have much lower costs.

In addition to the motor or engine, pump, and well, pumping plants include the valves, priming pumps when needed, suction pipe, and miscellaneous fittings. For any plant such items should be selected and their cost included in the cost estimate. For purposes of general cost comparisons, such smaller items usually

represent 5 to 15 per cent of the cost of the pump and driving power. The cost of transportation to the pump site may vary from $20 to $60 for usual conditions. The cost of installation varies usually from $25 to $100.

Pumping plants are usually enclosed in some form of housing. For belt-driven plants, housing covering the entire installation is generally used. The earlier deep-well installations usually retained the derrick over the well for use in pulling the pump for repairs. Such removal is now less frequently needed and derricks are generally removed after the completion of the construction of the plant. For direct-connected pumps, compact housing can be used. These may be of galvanized iron or may be made of any form of construction to harmonize with adjacent buildings. The housing should be well ventilated to avoid heating during operation. A compact type of housing over a deep-well turbine pump delivering into concrete-pipe standpipes is shown in Fig. 111. Usual costs of housing vary from $25 to $100.

FIG. 111.—Housing for direct-connected deep-well-turbine pump. Pump discharges into concrete-pipe standpipes.

Total Costs of Pumping Plants.—The following example illustrates the method of estimating the cost of installation of an irrigation pumping plant. A deep-well turbine pumping plant of 600 gal. per minute capacity is to be installed in a 14-in. well. Ground water stands 40 ft. below the ground, and the drawdown when pumping will be 18 ft. Water is to be delivered at the ground surface. The well has a total depth of 200 ft. with the pump set at 60 ft. below the ground to allow for possible future ground-water lowering. Electric power is to be used under the rate schedule in Table XXXVIII. The plant is to be operated 24 hr. a day for 20 days a month for 6 months.

An efficiency of 55 per cent based on static lift and the power delivered to the pump for all-season operation should be obtained. The brake horsepower required would be

$$\frac{600}{3,960} \times \frac{(40 + 18)}{0.55} = 16.0 \text{ hp.}$$

As motors may be operated at 10 per cent overload, a 15-hp. motor would be used.

The first cost of the plant would be as follows:

Well:	
Drilling 200 ft.—14-in. well at $1.50 per foot (Table XXIX	$ 300
200 ft. of 12-gage stovepipe casing at $2.50 per foot (Table XXX)	500
Pump, motor, and column (Table XXXVI)	850
Miscellaneous accessories	50
Freight and hauling	75
Installation	50
Housing	40
Total first cost	$1,865

This plant operates $24 \times 20 \times 6 = 2{,}880$ hr. per season and discharges

$$\frac{2{,}880}{12} \times \frac{600}{450} = 320 \text{ acre-feet}$$

The brake horsepower hours used equals $2{,}880 \times 16.0 = 46{,}160$. For a motor efficiency of 85 per cent, the power measured at the meter on the inlet side of the motor will be $46{,}160 \div 0.85 =$ 54,300 hp.-hr. or 40,500 kw.-hr. The power used equals 2,700 kw.-hr. for each of the 15 hp. of rated load.

The cost of operation would be as follows:

Power (Table XXXVIII):	
Demand charge at $5 per horsepower	$ 75.00
Service charge:	
15,000 kw.-hr. at 1.25 cts. per kilowatt-hour	187.50
15,000 kw.-hr. at 0.80 ct. per kilowatt-hour	120.00
10,500 kw.-hr. at 0.7 ct. per kilowatt-hour	73.50
Total power costs	$456.00
Fixed charges:	
13 per cent of $1,865	242.50
Attendance:	
120 days at $0.50 per day	60.00
Total costs of operation per year	$758.50

For the 320 acre-feet pumped per season the total costs of operation represent an average cost of $2.37 per acre-foot. In pumping for irrigation, a unit frequently used is the cost per foot

acre-foot which is the cost of pumping 1 acre-foot through a lift of 1 ft. For the plant used in the illustration the cost per foot acre-foot would be 4.1 cts. for the total of 18,660 feet acre-feet.

The demand charge may be based on the rating of the motor or on the actual load. For irrigation pumping, the motor rating is generally used. Where the actual load differs sufficiently from the motor rating, maximum-demand meters may be installed and the charges based on the maximum rate of power used for any 15- to 30-min. period. Such demand meters are of advantage to the consumer where motors are underloaded. The rules of most power companies permit the consumer to use a demand meter, a small charge for the use of meter being added to the power rate. In the preceding example the demand charge was based on the rated capacity of the motor. The kilowatt-hours used depended on the actual brake horsepower required.

The illustration brings out the importance of the items of cost other than the cost for the power used. Many using such plants neglect the fixed charges in their accounts for operating charges. Fixed charges and attendance are just as much a part of the actual costs of pumping as the cash outlay for power. In the example, such charges represent about 40 per cent of the total cost of operation. For plants operated for shorter periods of time, the fixed charges are a relatively larger proportion of the total costs.

Similar examples can be worked out covering costs for different capacities, lifts, and periods of operation. This has been done in Tables XL, XLI, XLII, and XLIII. The costs for installation and for power are representative of those applicable in central California. In other areas of less extensive pumping development, the costs of wells and equipment may be somewhat higher. Power rates may be higher or lower in other areas, depending upon local conditions; rates in other states are more usually higher per kilowatt-hour than those shown in Table XXXVIII, which were used in these comparisons.

The plants used were all deep-well turbine pumps except for the 20-ft. lifts, for which centrifugal pumps in pits were used. The costs include the drilling and casing of wells assumed to extend 100 ft. below the depth of ground water when pumping. The diameters of the wells were adjusted to the discharge. The costs also include hauling, accessories, installing, and housing.

In Table XL is shown the total cost of installation for three sizes of pumping plants for lifts up to 200 ft. These plants cover

the usual range of irrigation from wells. Few irrigation plants have capacities of less than 225 gal. per minute, more plants exceed 900 gal. per minute, but such discharge requires favorable ground-water conditions if excessive drawdown is to be avoided. Lifts of over 200 ft. require unusually profitable conditions of use to justify the costs of pumping.

TABLE XL.—TOTAL COSTS OF INSTALLATION FOR TYPICAL PUMPING PLANTS AND WELLS FOR CENTRAL CALIFORNIA CONDITIONS

Total pumping lift including draw-down in well, feet	Discharge of pump, gallons per minute		
	225	450	900
20	$ 850	$1,050	$1,400
50	1,200	1,550	1,850
75	1,550	1,950	2,400
100	1,900	2,350	2,800
150	2,500	3,100	3,600
200	3,150	3,700	4,500

Table XL shows that the cost of installing plants pumping from wells does not increase in proportion to the lift or the capacity. The capacity may be increased 300 per cent with an increase in cost of the plant of less than 100 per cent. The lift may be increased 300 per cent from 50 to 200 ft. with increases in cost of about 150 per cent.

COST OF OPERATION OF PUMPING PLANTS FOR CENTRAL CALIFORNIA CONDITIONS

The costs of operation, including power, fixed charges, and attendance for a 450 gal. per minute plant used to pump from 100 to 600 acre-feet per year are shown in Table XLI for lifts from 20 to 200 ft. The results in Table XLI are expressed in terms of costs of lifting an acre-foot of water 1 ft. in height. The first cost of the plant is similar to that shown in Table XL; the cost of power is based on rates similar to those in Table XXXVIII.

Like other equipment, the most economical operation is secured when pumping plants are operated a large proportion of the time. This results in a large output over which to distribute the fixed charges. Continuous operation throughout the year with a discharge of 450 gal. per minute will produce 724 acre-feet so that each 100 acre-feet pumped represents operation for about 14 per

cent of the available time. For the plant shown in Table XLI the average cost per foot acre-foot pumped when pumping 400 acre-feet per year is less than one-half the similar cost when pumping only 100 acre-feet per year.

TABLE XLI.—COST PER ACRE-FOOT LIFTED 1 FT. FOR PUMPING PLANT OF 450 GAL. PER MINUTE CAPACITY USING DEEP-WELL TURBINES FOR DIFFERENT LIFTS AND AMOUNT OF PUMPING

Lifts include drawdown. Costs include power, fixed charges, and attendance and are applicable to central California conditions

Total acre-feet pumped per season	Cost, cents per acre-foot lifted 1 ft. for total pumping lifts of				
	20 ft.	50 ft.	75 ft.	100 ft.	200 ft.
100	13.0	9.6	8.5	7.6	6.25
200	9.0	6.6	5.7	5.3	4.5
300	7.5	5.2	4.7	4.35	3.75
400	6.25	4.4	3.9	3.7	3.1
500	5.25	3.9	3.5	3.25	2.8
600	4.5	3.6	3.2	3.0	2.45

Table XLII shows total costs of pumping per acre-foot for similar conditions to those shown in Table XLI for costs per foot acre-foot. Table XLII shows that the cost per acre-foot for a plant pumping 500 acre-feet per year on a 100-ft. lift will be no larger than that for a plant having a lift of 50 ft., pumping only 100 acre-feet per year. Where sufficient area to be irrigated is available and where diversified crops can be grown, so as to result in a long seasonal demand for water, the cost per acre-foot pumped on a 200-ft. lift would not exceed that on a 50-ft. lift with a small amount of pumping. The cost per acre depends on the amount of water used, as well as the cost per acre-foot. While the cost per acre-foot for short periods of use may be high, the cost per acre may not be excessive if small amounts of supplemental irrigation only are required.

Table XLIII illustrates the cost of pumping for plants of different capacities and lifts with varying amounts of operation. The results in Table XLIII represent the conditions that would confront an owner, having a given demand for water and lift, who was selecting the size of plant to use. If a pumping supply of 200 acre-feet per year was needed with a lift of 50 ft., minimum costs would be secured with a 225 gal. per minute plant which would have to be operated 50 per cent of the total time during the

Table XLII.—Cost per Acre-foot under General Central California Conditions for Water Pumped from Wells for Different Lifts and Amount of Pumping for a Plant Having a Capacity of 450 Gal. per Minute

Lifts include drawdown. Costs include power, fixed charges, and attendance

Total acre-feet pumped per season	Costs per acre-foot for height of pumping in feet of				
	20	50	75	100	200
100	$2.60	$4.80	$6.35	$7.60	$12.50
200	1.80	3.30	4.30	5.30	9.00
300	1.55	2.60	3.50	4.35	7.50
400	1.25	2.20	2.90	3.70	6.20
500	1.05	1.95	2.60	3.25	5.60
600	0.90	1.80	2.40	3.00	4.90

year. Costs would be increased about 30 cts. per acre-foot or 10 per cent in total by using a 450 gal. per minute plant operated about one-fourth of the total time, the smaller amount of power used due to better efficiency and somewhat lower unit price for power and shorter period of attendance nearly balancing the larger fixed charges of the larger plant. A 900 gal. per minute plant would increase the cost per acre-foot about an additional 10 per cent. Where the ground water will furnish the increased discharge without increased lift, as assumed in Table XLIII, the advantages in irrigation with the larger discharge and the shorter time required to secure the desired supply would balance such increases in cost and the larger plant would be preferable. With a larger plant installed, lower costs per acre-foot could be secured by larger amounts of operation, as indicated in Table XLII.

LIMITS OF ECONOMICAL PUMPING

The limits of economical pumping vary with the returns obtained from the crops grown. As such returns vary, the feasible pumping lift also varies. Usual practice generally adjusts itself to average returns. Less efficient plants may cease operation during periods of low returns.

In general, the cost of water pumped from wells is higher than the cost of water delivered from gravity canal systems. Pumping from wells has been used mainly where canal supplies were not available or to supplement deficiencies in the canal supply at certain periods.

TABLE XLIII.—COST PER ACRE-FOOT FOR WATER PUMPED FROM WELLS FOR DIFFERENT LIFTS AND AMOUNTS OF OPERATION

Lifts include drawdown. Costs include power, fixed charges, and attendance. Results are applicable to general central California conditions

Total acre-feet pumped per season	Plant of 225 gal. per minute capacity			Plant of 450 gal. per minute capacity			Plant of 900 gal. per minute capacity		
	Lift of 20 ft.	Lift of 50 ft.	Lift of 100 ft.	Lift of 20 ft.	Lift of 50 ft.	Lift of 100 ft.	Lift of 20 ft.	Lift of 50 ft.	Lift of 100 ft.
100	$2.50	$4.50	$7.30	$2.60	$4.80	$7.60	$3.20	$5.30	$8.70
200	1.70	3.00	4.80	1.80	3.30	5.30	2.00	3.60	6.00
400	.....	.....	.....	1.25	2.20	3.70	1.50	2.60	4.30
600	.....	.....	.....	0.90	1.80	3.00	1.25	2.00	3.50
800	.....	.....	.....	.....	.....	.....	1.00	1.75	2.90
1,000	.....	.....	.....	.....	.....	.....	0.75	1.60	2.60

For crops of high returns, such as citrus, water has been pumped through total lifts of 500 ft. in some cases. Such lifts include the boosting to side-hill areas in addition to the lift from wells. There are some California plants in which the lift in the well exceeds 300 ft. Such pumping lifts represent an extreme and are practicable only where large returns are secured from the use of small amounts of water.

For alfalfa, which requires larger amounts of water and has smaller returns per acre, with small plants on individual farms, care in the use of water and conditions that result in yields and returns above the average are required if pumping with lifts of from 50 to 75 ft. is to be profitable. For annual crops, such as potatoes or sugar beets, the economical limit of pumping lift may be somewhat higher because of the smaller amount of water required. Relatively favorable conditions of cost, amount of water used, or return from the crops are necessary to make lifts of 100 ft. profitable. Such conditions are usually found only in the case of orchard crops.

An irrigation supply obtained by pumping from wells has some advantages over supplies secured from canals, which may justify somewhat higher cost for pumping. Among these are the ability to irrigate at the time desired rather than having to wait for delivery under a canal schedule, less shortage in late-summer supply, and freedom from weed seed in the water.

The conditions affecting irrigation pumping in different localities and in different parts of the same locality are variable and no development of ground water for a farm should be undertaken without a thorough consideration of the local factors. Such consideration should include the permanence and extent of the ground-water supply as well as the well and its equipment. Prospective profits at the time of installation of the pumping plant may not be realized if the costs are increased over those anticipated owing to the lowering of the ground water with the resulting increased lifts.

The illustrations of pumping costs that have been given are based on well-selected and maintained plants for conditions applicable in central California. The results represent costs that should be obtainable in this area. The costs shown, however, are lower than the average costs in central California, as average practice includes many plants not well selected in relation to their conditions of operation, having efficiencies lower than those used in preparing the tables shown. Costs in other states are frequently higher than those shown in these tables, owing both to the same factors and also to the generally higher cost of power in areas where pumping is less extensively practiced.

References

1. Etcheverry, B. A., and S. T. Harding: The Selection and Cost of a Small Pumping Plant, *California Agr. Exp. Sta. Circ.* 117, 1923.
2. Moses, B. D., and L. S. Wing: Farmers Purchase Agreement for Deep Well Pumps, *California Agr. Exp. Sta. Bull.* 448, 1928.
3. Code, W. E.: The Cost of Pumping for Irrigation in Colorado, *Colorado Agr. Exp. Sta. Bull.* 387, 1932.
4. Powers, W. L.: The Economic Limit of Pumping for Irrigation, *Oregon Agr. Exp. Sta. Bull.* 235, 1928.
5. Bixby, F. L., and George Hardman: Development of Water Supplies for Irrigation in Nevada by Pumping from Underground Sources, *Nevada Agr. Exp. Sta. Bull.* 112, 1928.
6. Smith, L. J., and H. L. Garver: Irrigation West of the Cascade, *Washington Agr. Exp. Sta. Popular Bull.* 140, 1928.
7. Standards of the Hydraulic Society, 1931.

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